

SHORTENING ESTIMATE OF POST-TENSIONED MEMBERS¹

Bijan O Aalami²

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P.1 OVERVIEW

In post-tensioned construction, the tendons are stressed and anchored after the concrete member they are embedded in has developed sufficient strength (Fig. P.1-1a). The tension in the tendons results in an equivalent compression in the concrete, which causes the member to shorten (Fig. P.1-1b). In most applications, the tendons are profiled so that they also exert a vertical force on the member (Fig. P.1-1c). The vertical force results in a bending moment in the member; the tendon profile is usually selected to counteract the bending of the member under selfweight, thus reducing the bending under normal loading. This Technical Note deals with the shortening of a post-tensioned member caused by the precompression; the possible restraint of the member's supports to shortening; the possibility of crack formation in the member from this restraint; and finally the evaluation of restraint cracks.

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² Professor Emeritus, San Francisco State University; Principal, ADAPT Corporation; www.adaptsoft.com



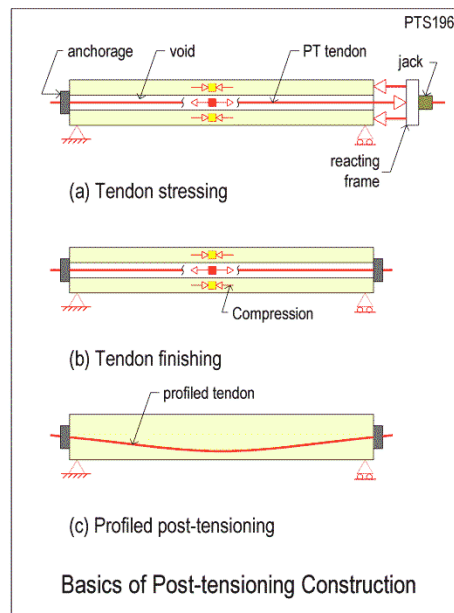


FIGURE P.1-1 Basics of Post-Tensioning Construction

Because concrete is not a completely rigid material, the post-tensioning force P will compress a free-standing concrete member, and shorten it. The compressive stress f resulting in the member from the application of the force P leads to the member's shortening u . The relationship between the compressive stress in the member and its shortening is governed by the material properties of the member and is generally similar to Fig. P.1-2a .

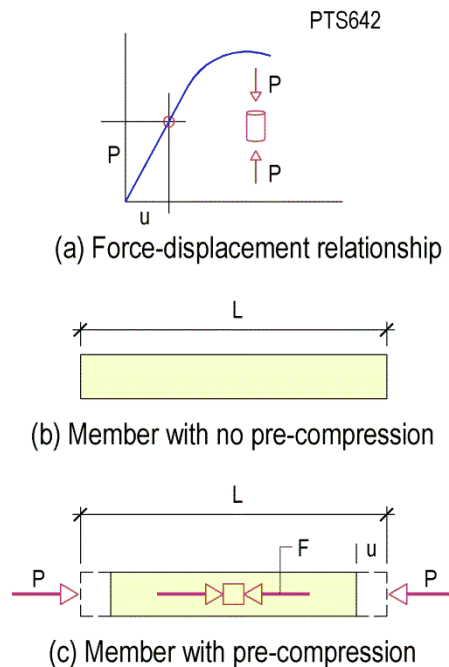


FIGURE P.1-2 Precompression and Shortening

In actual construction, post-tensioned members such as floor slabs and beams are supported on walls and columns. These supports can restrain the free shortening of the member when the tendons are stressed. Unless the member is allowed to shorten, as shown in Fig. P.1-3, it will not receive the full amount of precompression from the stressed tendons. In theory, if the supports prevent any shortening (part b of the figure), the entire post-tensioning force will be diverted to the supports, leaving the member with no precompression. Failure to account for restraint from the supports can lead to cracking. Apart from possible aesthetic objections, these restraint cracks can cause leakage, and expose the reinforcement to the corrosive elements. More importantly, restraint cracks can reduce the contribution of the post-tensioning tendons to the strength capacity of the member.

The extent of the restraint cracking in a post-tensioned member depends on a number of factors, including the stiffness of the supports. Figure P.1-4 illustrates two extremes. In part (a) a post-tensioned member on very flexible supports shortens under the precompression, forcing the supports to follow the member's moment. This can result in cracking of the supports. At the other extreme, a member on very stiff supports will be restrained against in-plane shortening and can develop restraint cracks as it shortens (part b of the figure).

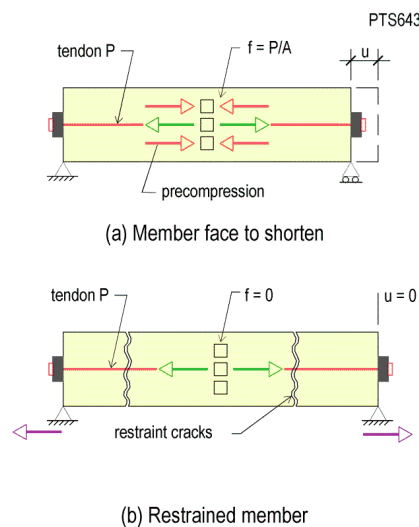


FIGURE P.1-3 Restrainted and Unrestrained Members

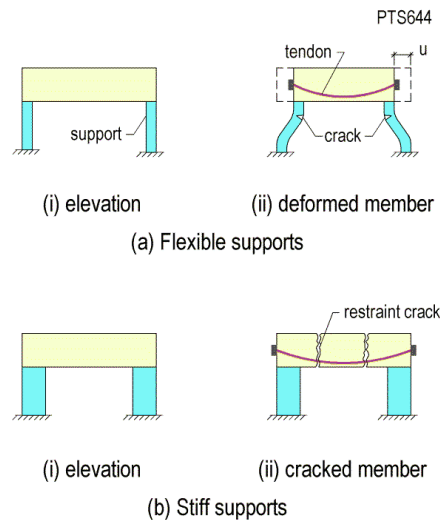


FIGURE P.1.4 Effects of Support Restraint on Member Cracking

Cracking due to restraint from the supports is generally most pronounced at the first level of a structure, due to the restraint from the foundation; there is less cracking at higher levels. Experienced design engineers are aware of the possibility of restraint cracking and its consequences; they use a number of measures to allow the post-tensioned member to shorten, while minimizing the effects of cracking in either the member or its supports.

The first step in designing for shortening and restraint cracking of a post-tensioned member is to either calculate or estimate the anticipated long-term shortening. Section P.2 outlines a computational procedure to determine the long-term shortening of a post-tensioned member. The outlined procedure is based on ACI 423 [ACI 423, 1979]. Section P.3 discusses the details commonly used to reduce the potential for restraint cracking. Section P.4 provides a guideline to estimate shortening for preliminary design and goes through two examples that illustrate the practical aspects of design for crack mitigation. Section P.5 describes the consequences of restraint cracks on the safety of a post-tensioned member and highlights the significance of the type of post-tensioning (bonded or unbonded).

P.2 COMPUTATION OF SHORTENING

The long-term shortening of a post-tensioned member is primarily the result of:

- ❖ Shrinkage;
- ❖ Creep;
- ❖ Elastic shortening; and
- ❖ Temperature change.

Much is available in the literature on the contribution of each of the above parameters and the interactions among them. Most of the literature on shortening of concrete members is based on test specimens observed in the controlled environment of research laboratories. The environment of an actual structure will not match that of these test specimens, however. While it is possible to estimate shortening by taking a test specimen from the concrete of the actual structure and curing it in the same environment as the structure, this is not often done. Testing would provide useful data for other structures under the same conditions but would not help with design of the structure being tested. The typical practice is to

start with the base values observed in the laboratory specimen and adjust them to reflect the conditions of the actual structure. The adjustment is done by applying various correction factors, each of which accounts for one of the variations between the environment of the actual structure and the environment of the standard test specimen.

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- ❖ The effects of each of the shortening components are independent from one another and can be estimated on their own.
- ❖ The parameters of the structure are within the applicable range of the suggested correction factors. These are:
 - Concrete weight: $W = 140 - 155$ pcf (2300 - 2600 kg/m³)
 - Concrete strength (28 day cylinder): $f'_c = 3000$ to 6000 psi (21 to 40 MPa)
 - Average precompression: $P/A = 100$ to 350 psi (0.8 to 2.40 MPa)

The total shortening of a post-tensioned member meeting the above criteria can be expressed as follows:

$$a = L (ES + SH + CR + TEM) \quad (\text{Exp P.2-1})$$

Where,

- a = total shortening;
- CR = creep shortening strain;
- ES = elastic shortening strain;
- L = length of the member; and
- SH = shrinkage shortening strain; and
- TEM = strain due to drop in temperature.

The creep and shrinkage values obtained through laboratory tests are referred to as the “base shrinkage strain” SH_o and “base creep coefficient” CR_o . Strain is a dimensionless quantity, with units of length/length (inch/inch or mm/mm). Because strains are typically quite small, they are usually measured in micro-strains, where a micro-strain is a strain of 1×10^{-6} .

The base shrinkage strain reflects the total reduction in length over the original length of the concrete specimen if the specimen is allowed to freely shorten over an infinite length of time, under constant pre-defined ambient conditions. The base creep coefficient is the ratio of the long-term shortening to the elastic shortening of a concrete specimen that is loaded at a given age and allowed to shorten without restraint under controlled ambient conditions.

P.2.1 Shortening from Shrinkage

Shrinkage is caused by the loss of moisture from the concrete and is independent of applied stress. In most cases, shrinkage is the largest contributor to floor shortening. In the absence of laboratory tests or code-recommended values, the base shrinkage strain (SH_0) can be assumed to be 500 to 600 micro-strain for water-to-cement ratios between 0.4 to 0.45.

The base shrinkage strain must be adjusted for the ambient relative humidity (k_{RH}) and the volume-to-surface ratio of the member ($k_{v/s}$).

$$SH = SH_0 \times k_{RH} \times k_{v/s} \quad (\text{Exp P.2.1-1})$$

Adjust the base shrinkage strain by the coefficient k_{RH} given in the following Table.

TABLE P.2.1-1 Factors for Correction of Base Shrinkage for Relative Humidity (T188)

Relative Humidity	40	50	60	70	80	90	100
k_{RH}	1.43	1.29	1.14	1.00	0.86	0.43	0.00

Members with higher volume-to-surface (V/S) ratios will lose less moisture and therefore tend to shrink less. Solid flat slabs, for example, will shrink less than waffle slabs. The recommended base shrinkage strain is based on a volume-to-surface ratio of 1.5 inch (38 mm). Use the following relationships to adjust the base shrinkage for other cross-sections:

The base shrinkage strain recommended was based on a volume to surface ratio equal to 1.5 inch (38 mm). Use the following relationships to adjust the base shrinkage for other cross-sections:

$$k_{v/s} = [1064 - 94(V/S)]/923 \quad \text{US units (V/S is calculated in inches) (Exp P.2.1-2)}$$

$$k_{v/s} = [1064 - 3.7(V/S)]/923 \quad \text{SI units (V/S is calculated in mm) (Exp P.2.1-3)}$$

The surface area used in determining the volume to surface area should include only the area that is exposed to atmospheric drying. For poorly ventilated enclosed cells, only 50% of the interior perimeter should be used in calculating the surface area.

Example: P.2.1-1

Calculate the volume to surface ratio of the following sections:

(i) Slab of uniform thickness h

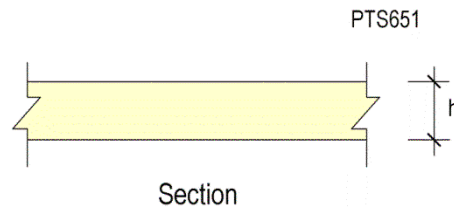


FIGURE P.2.1.1-1 Member with Uniform Thickness

For a strip of unit width:

$$V/S = (1 \times h) / (2 \times 1) = h/2$$

Hence, for a 10 in. (250 mm) slab, $V/S = 5$ in. (125 mm)

(ii) Waffle slab with the following dimensions for each waffle:

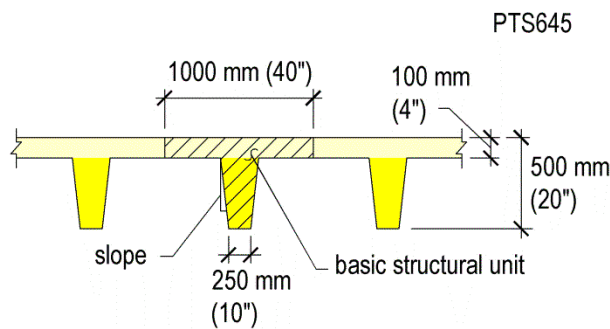


FIGURE P.2.1.1-2 Section; Waffle Slab

Given

- Width = 1000 mm (40 in.)
- Depth = 500 mm (20 in.)
- Stem width = 250 mm (10 in.)
- Flange depth = 100 mm (4 in.)

Solution

$$V = 1000 \times 100 + 250 \times 400 = 200000 \text{ mm}^2$$

$$S = 1000 \times 2 + 400 \times 2 = 2800 \text{ mm}$$

$$V/S = 200000 / 2800 = 71.43 \text{ mm (2.81 in.)}$$

Example P.2.1-2

For a base shrinkage strain of 550 micro strain, what is the long-term shrinkage strain (SH) of a 250 mm (10 in) slab of uniform thickness at a location with an ambient relative humidity $H=80\%$.

Shrinkage strain, $SH = SH_0 \times k_{RH} \times k_{v/s}$

$$SH_0 = 550 \times 10^{-6}$$

$$k_{RH} = 0.86 \quad [\text{From Table P.2.1-1}]$$

$$V/S = h/2 = 250/2 = 125 \text{ mm (5 in.)}$$

$$k_{v/s} = [1064 - 3.7 (V/S)]/923 =$$

$$= [1064 - 3.7 \times 125]/923 = 0.65 \quad \text{SI units (mm)}$$

$$k_{v/s} = [1064 - 94 (V/S)]/923 =$$

$$= [1064 - 94 \times 5]/923 = 0.64 \quad \text{US units (inch)}$$

$$\text{Shrinkage strain, } SH = 550 \times 10^{-6} \times 0.86 \times 0.65 = 307 \times 10^{-6}$$

P.2.2 Shortening from Creep

Creep is primarily a function of applied stress. Creep shortening of concrete under a sustained load is generally between 1.5 to 4.0 times the initial elastic shortening; the actual value is predominantly dependent on the age of the concrete when the load is applied. The base creep coefficient, CR_0 generally used for the post-tensioned floor systems in the US, where tendons are typically stressed to their full value three to four days after the concrete is cast, is 2.0. An upper bound value of 2.5 is recommended.

The base creep coefficient CR_0 selected for a floor system must be modified to account for the particulars of the building under consideration.

$$CR_c = CR_0 \times K(PT) \times k_f \times k_{cRH} \times k_c$$

Where,

CR_c = creep coefficient;

CR_0 = base creep coefficient;

$K(PT)$ = correction factor for the average precompression from post-tensioning;

k_f = correction factor for concrete strength;

k_{cRH} = correction factor for the ambient humidity; and

k_c = correction factor for volume to surface ratio.

The correction factor $K(PT)$ is 1.0 for the average precompression values commonly used in buildings (125 to 300 psi; 0.84 to 2 MPa) and the commonly used concrete strengths. This simplifies the calculation of shortening due to creep effects to the following:

$$CR_c = CR_0 \times k_f \times k_{cRH} k_c \quad (\text{Exp P.2.2-2})$$

The other correction factors are:

$$k_f = \frac{1}{0.67 + \frac{f_c^i}{9}} \quad (\text{US units; } f_c^i \text{ in ksi}) \quad (\text{Exp P.2.2-3})$$

$$k_f = \frac{62}{42 + f_c^i} \quad (\text{SI units, } f_c^i \text{ in MPa}) \quad (\text{Exp P.2.2-4})$$

$$k_{cRH} = (1.58 - H/120) \quad (\text{Exp P.2.2-5})$$

Where, H is the ambient relative humidity at project location.

The primary impact of the volume-to-surface ratio on creep shortening is during the first few months, when the creep of concrete is more significant. The impact of volume to surface ratio on the long-term creep of a member is not as significant. The following relationships give the adjustment to the base creep coefficient:

$$k_c = \left[\frac{1.80 + 1.77 e^{-0.54(V/S)}}{2.587} \right] \quad (\text{US units; in.}) \quad (\text{Exp P.2.2-6})$$

$$k_c = \left[\frac{1.80 + 1.77 e^{-0.0213(V/S)}}{2.587} \right] \quad (\text{SI units; mm}) \quad (\text{Exp P.2.2-7})$$

P.2.3 Elastic Shortening

Elastic shortening is an immediate response of a member to compression. To estimate elastic shortening, the precompression is calculated using the average force of the tendons over the length of a member divided by the member's cross-sectional area tributary to the tendons. In practice, the average force over the design strip³ is used in the calculation.

Average strain due to elastic shortening is:

$$ES = (P/A)/E_{ci} \quad (\text{Exp P.2.3-1})$$

Where,

- ES = total strain due to average elastic shortening;
- P = average value of prestressing force allowing for friction losses, but not long-term stress losses⁴;
- A = cross-sectional area of the member's tributary; and
- E_{ci} = modulus of elasticity of the concrete at the time of stressing.

³ A design strip would be a beam with its entire tributary or a line of column supports with their tributary area on either side.

⁴ When tendons are stressed one after the other, the force in previously stressed tendons will decrease as subsequent tendons are stressed and cause elastic shortening of the member. Since the relationship is based on average precompression, it is not necessary to adjust for the stressing sequence.

A. Designs Based on US Codes. There are two methods commonly used.

For design in the US, E_{ci} is typically calculated as⁵:

$$E_{ci} = 33W_c^{1.5} \sqrt{f'_{ci}} \quad \text{in US units}$$

f'_{ci} = compressive strength of concrete cylinder at time of stressing, psi;
 W_c = weight of one cubic ft of concrete, between 90 and 155 lb/ft³; and
 E_{ci} = modulus of elasticity of concrete at day of stressing, psi.

In SI units the relationship is:

$$E_{ci} = 0.043W_c^{1.5} \sqrt{f'_{ci}} \quad (\text{Exp P.2.3A-2})$$

Where,

E_{ci} is in MPa; W_c in kg/m³ and f'_{ci} in MPa

Usually the cylinder strength at stressing will be known; most project specifications prohibit stressing the tendons until the concrete reaches a minimum cylinder strength specified in the project's specifications. If the cylinder strength at stressing is not available, the following relationship can be used to estimate f'_{ci} :

$$f'_{ci} = \frac{1.45t^{0.75}}{t^{0.75} + 5.5} f'_c \quad (\text{Exp P.2.3A-3})$$

B. Design Based on European Code EC2: Using EC2 the modulus of elasticity of concrete cylinder at 28 days E_c is given by:

$$E_c = 22 \times 10^3 \left[\frac{(f_{ck} + 8)}{10} \right]^{0.3} \quad \text{in SI units} \quad (\text{Exp P.2.3B-1})$$

The modulus of elasticity on day (t) is given by:

$$E_c(t) = \left[\frac{f_{cm}(t)}{f_{ck} + 8} \right]^{0.3} E_c \quad \text{in SI units} \quad (\text{Exp P.2.3B-2})$$

Where.

$$f_{cm}(t) = \exp \left\{ s \left[1 - \left(\frac{28}{t} \right)^{0.5} \right] \right\} (f_{ck} + 8) \quad (\text{Exp P.2.3B-3})$$

⁵ ACI 318-11, Section 8.5.1

$f_{cm}(t)$ = mean compressive strength of concrete cylinder on day “ t ,”
 t = age of concrete in days; and
 s = a coefficient which depends on the type of cement, (this is 0.2 for most common cements).

P.2.4 Temperature Effects

Temperature effects are reversible, depending on whether there is a rise or fall in temperature. As a result, they are generally not considered when calculating the long-term shortening of a floor slab. However, in cases of exposed structures such as parking garages where there are seasonal extremes in the temperature, the effects can be quite significant and should be accounted for. The change in the length of a member is given by:

$$d = L \times T \times \alpha \quad (\text{Exp P.2.4-1})$$

Where,

d = change in length;
 T = change in temperature (degrees F or C); and
 α = coefficient of thermal expansion.

In the absence of more precise data, the coefficient of thermal expansion of concrete can be taken as:

$$\alpha = 6.0 \times 10^{-6} / F^{\circ}$$

$$\alpha = 10.1 \times 10^{-6} / C^{\circ}$$

P.2.5 Shortening Example

Estimate the long-term shortening of the following post-tensioned slab.

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Concrete	5000 psi	(34 MPa)
Slab thickness	8 inch	(200 mm)
Length of the slab	100 ft	(30 m)
Relative humidity H	75%	
Average precompression	150 psi	(1.0 MPa)
Stressing day	3 day	(3 day)
Seasonal change in temperature	25 F°	(14 C°)

REQUIRED

Total long-term unrestrained change in length

In the absence of more accurate data, the following somewhat conservative assumptions can be used for the base values⁶. These values are applicable for most areas, unless the concrete is of poor quality, in which case higher values are recommended.

$$\text{Base shrinkage strain } SH_0 = 600 \times 10^{-6}$$

$$\text{Base creep coefficient } CR_0 = 2.5$$

Elastic shortening strain, *ES*:

$$ES = (P/A)/E_{ci}$$

The concrete strength at stressing (f'_{ci}) is not known so must be estimated from its specified (28-day) strength.

$$f'_{ci} = \frac{1.45t^{0.75}}{t^{0.75} + 5.5} f'_c$$

$$f'_{ci} = \frac{1.45 \times 3^{0.75}}{3^{0.75} + 5.5} 5000 = 2124 \text{ psi (14.64 MPa)}$$

$$E_{ci} = 33 \times 150^{1.5} \sqrt{2124} = 2794010 \text{ psi (19264 MPa)}$$

Hence, the elastic shortening strain of the slab is:

$$ES = (P/A)/E_{ci}$$

$$ES = 150 / 2794010 = 54 \times 10^{-6}$$

Shrinkage shortening strain, *SH*:

$$SH = SH_0 \times k_{RH} \times k_{v/s}$$

From table P.2.2-1, the correction for relative humidity $H=75\%$ is interpolated from the given values.

$$k_{RH} \text{ for } 70\% = 1.00$$

$$k_{RH} \text{ for } 80\% = 0.86$$

$$k_{RH\ 75} = 1.00 - 0.5(1.00 - 0.86) = 0.93$$

Correction for volume-to-surface ratio:

⁶ For structures in USA, and where strict quality control is exercised, assume base creep coefficient = 2 and base shrinkage strain = 400 micro strain

$$V/S = 0.5 \times 8 = 4 \text{ in.} \quad (0.5 \times 200 = 100 \text{ mm})$$

The correction factor $k_{v/s}$ is:

$$k_{v/s} = [1064 - 94 \times 4] / 923 = 0.75 \quad \text{US units}$$

$$k_{v/s} = [1064 - 3.7 \times 100] / 923 = 0.75 \quad \text{SI units}$$

Hence the long-term shrinkage strain is:

$$SH = 600 \times 10^{-6} \times 0.93 \times 0.75 = 419 \times 10^{-6}$$

Creep shortening strain, CR :

$$CR = CR_c \times ES$$

$$CR_c = CR_0 \times k_f \times k_{cRH} \times k_c$$

Correction for concrete strength k_f ;

$$f'_c = 5000 \text{ psi (34 MPa)}$$

$$k_f = 1 / (0.67 + 5/9) = 0.82 \quad \text{(US units)}$$

$$k_f = 62 / (42 + 34) = 0.82 \quad \text{(SI units)}$$

Correction for relative humidity

$$k_{cRH} = (1.58 - H/120)$$

$$k_{cRH} = (1.58 - 75/120) = 0.96$$

Correction for the volume-to-surface ratio:

$$V/S = 0.5 \times 8 = 4 \text{ in.} \quad (0.5 \times 200 = 100 \text{ mm})$$

The correction factor k_c is:

$$k_c = (1.80 + 1.77 \times e^{-0.54 \times 4}) / 2.587 = 0.77 \quad \text{(US units)}$$

$$k_c = (1.80 + 1.77 \times e^{-0.0213 \times 100}) / 2.587 = 0.78 \quad \text{(SI units)}$$

Having obtained the correction factors, the creep coefficient is given by:

$$CR_c = 2.5 \times 0.82 \times 0.96 \times 0.78 = 1.54$$

$$CR = CR_c \times ES = 1.54 \times 54 \times 10^{-6} = 83 \times 10^{-6}$$

Total shortening, without taking temperature effect into account:

$$a = L (ES + SH + CR)$$

$$a = 100 \times 12 \times (54 + 419 + 83) \times 10^{-6} = 0.67 \text{ in. (17 mm)}$$

Temperature effect:

$$d = L \times T \times \alpha = 100 \times 12 \times 25 \times 6.0 \times 10^{-6} = 0.18 \text{ in. (4.6 mm)}$$

Total shortening including temperature effect:

$$= 0.67 + 0.18 = 0.85 \text{ in. (22 mm)}$$

P.2.6 Estimate of Short-Term Shortening

The short-term shortening of a post-tensioned member can be important when designing for crack mitigation. The amount of shortening at a given time can be estimated from the expected long-term shortening. For the shortening due to creep and shrinkage the following graph can be used [PTI, 1988].

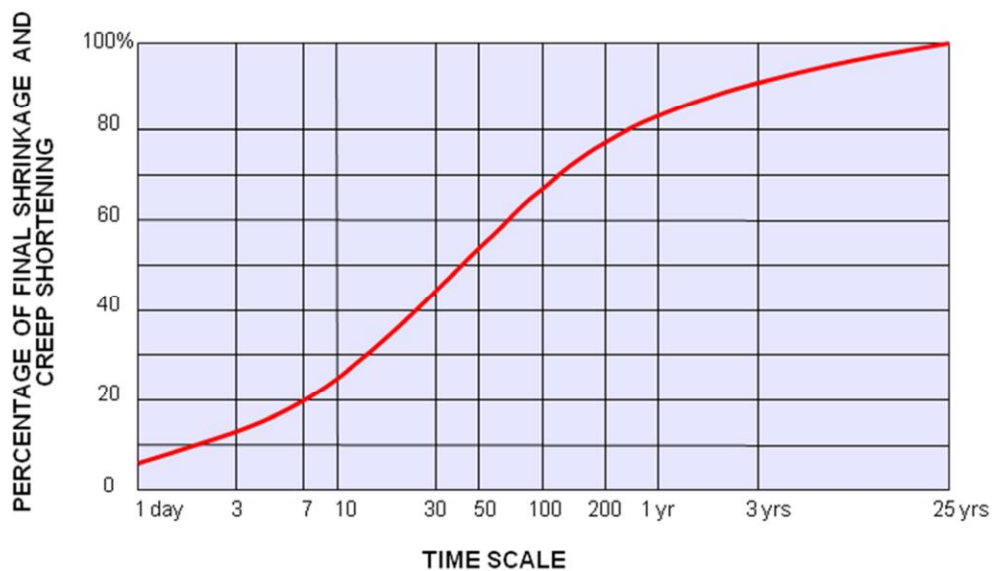


FIGURE P.2.7-1 Variation of the Combined Creep and Shrinkage Shortening with Time for Typical Post-Tensioned Members (P569)

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P.8 NOTATIONS

A = cross sectional area of concrete associated with tributary of prestressing force P , in², mm²;

a = total shortening of a member, in, mm;

CR = contribution of creep strain to shortening (Non-Dimensional ND);

CR_0 = base creep coefficient, ND;

CR_C = creep coefficient, ND;

d = change in length of a member;

E_c = modulus of elasticity of concrete on day 28, psi, MPa;

E_{ci} = modulus of elasticity of concrete on day of stressing, psi, MPa;

ES = total strain due to average elastic shortening;

f'_c = 28 day concrete cylinder strength, psi, MPa;

f'_{ci} = concrete cylinder strength on day of stressing, day t , psi, MPa;

$f_{cm}(t)$ = mean concrete compressive strength at an age of t days;

k_c = volume to surface correction factor for CR_0 , ND;

k_{cRH} = correction factor for CR_0 for ambient relative humidity, ND;

k_f = correction factor for CR_0 for concrete strength, ND;

$k(PT)$ = correction factor for CR_0 for the average precompression from post-tensioning, ND;

$k_{v/s}$ = correction factor for base shrinkage for volume to surface ration (V/S), ND;

L = total length of a member, ft, m;

P = prestressing force; lb, kN;

S = exposed surface area of a typical unit length of concrete member, in², mm²;

SH = contribution of shrinkage strain to shortening (Non-Dimensional ND);

-
- s = a coefficient which depends on the type of cement, ND;
- t = age of concrete in days;
- T = change in temperature, C⁰, F⁰;
- V = concrete volume of a typical unit length of concrete member, in³, mm³;
- W = unit weight of concrete, pcf, kg/m³;
- α = coefficient of thermal expansion. / C⁰, /F⁰;

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