Evaluation of Transverse Flange Forces Induced by Laterally Inclined Longitudinal Post-Tensioning in Box Girder Bridges

Walter Podolny, Jr.
Bridge Division
Office of Engineering
Federal Highway Administration
Washington, D.C.

Post-tensioned concrete box girders have become a common type of construction in current bridge technology. The advantages of box girders, as opposed to more conventional T-girder or precast I-girder construction, are due to a more favorable torsional stiffness with better load distribution properties, greater efficiency with respect to longitudinal bending, and improved aesthetic appearance.

The aesthetic appeal is further enhanced by inclined webs because of their streamlined appearance. In addition, the reduced soffit width reduces dead weight and reduces the width of supporting piers resulting in substructure economies.

For these reasons, a large number of contemporary box girder bridge designs have adopted inclined webs. However, because longitudinal post-tensioning tendons are placed in the inclined webs, the planes encompassing the tendon profiles will be parallel to the webs. Therefore, the post-tensioning force will produce secondary lateral and vertical component forces in the girder cross section [Fig. 1(a)].

A schematic distribution of lateral force, $q_a$, in plan, is shown in Fig. 1(b) and (c) for a simple span and a continuous span, respectively. This distribution assumes jacking from both ends and has not considered friction loss along the tendon length. Obviously, when friction is considered the distribution will not be uniform.
The magnitude of transverse secondary forces or stresses could be such as to produce cracking in the box girder flanges (Fig. 2). Cracking has been observed in some bridges which can wholly or partially be attributed to the effect of inclined tendon profiles. Transverse stresses are introduced into box girder bridges from dead and live loads, torsion, thermal gradient, and other factors. However, this paper will only consider the lateral effects induced in the flanges as a result of longitudinal prestressing in laterally inclined planes.

**TENDON PROFILE**

The tendon profile is generally presented in design drawings on a vertical elevation of the girder (Fig. 3). The tendon offset or sag is then the value of $f$. However, where the tendons are placed in an inclined plane, the geometry of the tendon profile must be determined with respect to that inclined plane to reflect the actual friction losses.

Tendon offset in the inclined plane (see Fig. 3) is determined as:

$$f_0 = f_0 / \sin \beta$$  (1)

from which the tendon radius of curvature, $R_0$, in the inclined plane, can be determined from:

$$R_0 = (4f_0^2 + c^2)/8f_0$$  (2)

where $c$ is the chord length of the profile curve. In the case of a simple span, the chord length is equal to the span length.

**TENDON FORCE AFTER FRICTION LOSS**

Having determined the tendon geometry with respect to the inclined plane, the tendon force after friction loss can be determined in a conventional manner from the following equation:

$$T_o = T_x (1 + KL + \mu \alpha)$$  (3b)

where

- $T_o = \text{steel stress or force at jacking end}$
- $T_x = \text{steel stress or force at any point } x$
- $e = \text{base of Naperian logarithms}$
- $K = \text{friction wobble coefficient per foot of prestressing tendon}$
- $L = \text{length of prestressing steel element from jack end to point } x$
- $\mu = \text{friction curvature coefficient}$
- $\alpha = \text{total angular change of}$

A large number of contemporary box girders have a trapezoidal cross section. Because the webs are laterally inclined, the longitudinal post-tensioning profile plane is parallel to the webs. Therefore, the post-tensioning force will produce secondary lateral and vertical component forces in the cross section. This paper considers only the lateral effects induced in the flanges as a result of longitudinal prestressing in laterally inclined planes.

With the possible exception of external tendons, the stresses induced in the flanges by these secondary forces are generally small when taken alone. However, when superimposed upon other stresses, or if other potential cracking mechanisms are present, distress in the form of cracking may be precipitated. These lateral forces have been wholly or partially attributed to cracking in some bridges.

The proposed design procedure is illustrated with two numerical examples, one for a simple span girder and the other for a continuous girder together with the special case of external tendons.
Fig. 1. Lateral load distribution.
prestressing steel profile (in its laterally inclined plane) in radians from jacking end to point x

Values for $K$ and $\mu$ are tabulated in Ref. 2.

The formulas given above for tendon force, accounting for friction, are valid for straight girders and account for friction produced by curvature of the tendon in the plane of the tendon profile. For horizontally curved girders, the additional friction produced by curvature in the horizontal plane has to be considered. A method of including this effect is given as follows:

Since the total angle change due to horizontal curvature is a function of the horizontal radius, $R_h$, and the length along the curve, it is convenient to introduce a modification of the $KL$ term rather than the $\mu \alpha$ term of the expression $(KL + \mu \alpha)$.

Let $\alpha' = \text{horizontal angle change in radians per foot}$

$K' = \mu \alpha' = \text{modification factor considering the effect of horizontal curvature of friction}$

Then the expression $KL + \mu \alpha$ can be written as:

$$KL + \mu \alpha + \mu \alpha' L$$

or as:

$$\mu \alpha + L(K + K')$$

Therefore, the basic equations [Eqs. (3a) and (3b)] are modified as follows:

$$T_e = T_{e0} \left[ \frac{\mu \alpha + L(K + K')}{\mu \alpha + L(K + K')} \right]$$

When the expression $[\mu \alpha + L(K + K')] \leq 0.3$, the following equation may be used:
Values of $\alpha'$ and $K'$ for various horizontal curve radii are given in Table 1 where the values of $K'$ are based on galvanized rigid duct with $\mu = 0.25$.

The value of $\alpha'$ is a function of the horizontal radius of curvature, $R_h$, of the horizontal tendon profile, i.e., the web curvature. For inclined webs the value of $R_h$ may be determined, with minimal error, at the midheight of the tendon profile, i.e., $f_i/2$ or $f/2$, for the web under consideration.

GENERAL CABLE THEOREM

When a freely hanging cable, such as used in cable roof structures or cable stays, is subjected to a statically applied load in the plane of the cable curve and the length and shape of the cable under load is known, the maximum tension in the cable, the elongation and the change of shape of the cable can be determined. This section discusses the general solution to this problem.
Table 1. Select evaluation of $K'$ factor

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<th>$R_h$</th>
<th>$\alpha'$</th>
<th>$K'$</th>
<th>$R_h$</th>
<th>$\alpha'$</th>
<th>$K'$</th>
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<td>900</td>
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<td>5000</td>
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</tr>
<tr>
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<td>0.0013</td>
<td>0.0003</td>
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</table>

The following section will apply this solution to the special case of a post-tensioned tendon where the tension in the tendon and its geometry are known and the distributed loading along the tendon profile, in its plane, is to be determined. It should be noted that the term “tendon” as used in prestressing, for purposes of this discussion, is interchangeable with the term “cable” as used in other types of structures.

A general cable theorem can be stated as follows:\(^3\)

At any point on a cable supporting gravity loads only, the product of the horizontal component of cable tension and the vertical distance from that point to the cable chord equals the bending moment which would occur at that section if the gravity loads were acting on a beam of the same horizontal span as that of the cable.

Therefore, if $q$ is a uniformly distributed load (Fig. 4), the maximum bending moment at midspan is stated as:

$$M = q c^2 / 8$$

Hence

$$H f = q c^2 / 8$$

or

$$H = q c^2 / 8 f$$

and

$$q = 8 H f / c^2$$

The ordinate of the cable curve, $y$, may be derived at any point on the cable as follows:

Let $H = q c^2 / 8 f$ and $M_x = q x (c - x) / 2$.

Substituting in the general cable theorem $H y = M_x$ to obtain:

$$q c^2 y / 8 f = q x (c - x) / 2$$

$$y = 4 f (c x - x^2) / c^2$$

This is an equation for a parabola. The absolute value of the maximum slope is given by:

$$\left( dy / dx \right)_{x = 0, x = c} = 4 f (c - 2 x) / c^2 = 4 f / c = 2 f / (2 c)$$

which is shown graphically in Fig. 4.

If the value of cable tension at the support, $T$, is known, the value of the horizontal component, $H$, can be determined as follows:

$$\cos \theta = (c / 2) / [(c / 2)^2 + (2 f)^2]^{1/2}$$

$$= 1 / [1 + 16 (f / c)^2]^{1/2}$$

$$H = T \cos \theta = T / [1 + 16 (f / c)^2]^{1/2}$$

APPLI CATION OF GENERAL THEOREM TO A TENDON PROFILE

Eq. (8) gives the uniform load for a cable with a given tension at the support, a given chord length $c$ and a given sag $f$ for a freely hanging cable. In a post-tensioned tendon the cable is acted upon by friction. Therefore, the load $q$ for a post-tensioned tendon will not be uniform, as depicted in Fig. 4, but will vary along the cable.

Consider the condition depicted in Fig. 5 whereby the tendon force, $T_x$, at any point $x$ is determined considering the effects of friction from Eqs. (3) or (4).
Then from Eq. (9):

$$y = 4f(cx - x^2)/c^2$$

The cable offset, $f'$, with respect to the coordinates $x$ and $y$ is:

$$f' = f - y = f - [4f(cx - x^2)/c^2]$$

The chord length $c$ depicted in Fig. 4 in relation to the cross hatch area in Fig. 5 becomes $c' = c - 2x$.

The term $f/c$ in Eq. (10) with relation to any point $x$ becomes:

$$f'/c' = (f - [4f(cx - x^2)/c^2])/(c - 2x)$$

$$= f(c - 2x)/c^2$$

and

$$(f'/c') = f(c - 2x)/c^2$$

From Eq. (10):

$$T_{sh} = T/[1 + [16f^2(c - 2x)^2/c^2]^{1/2}]$$

From Eq. (8):

$$q_x = 8T_{sh}f'(c')^2$$

$$= 8fT/[c^4 + 16f^2(c - 2x^2)^2]^{1/2}$$

For the case when $x = c/2$:

$$q_x = 8fT/(c^4)^{1/2} = 8fT/c^2$$

which corresponds with Eq. (8).

For an inclined plane, the term $f_x$ (see Fig. 3) would be substituted for the $f$ term in Eqs. (11), (12) and (13).

**LATERAL LOAD INDUCED IN FLANGES**

Having determined the distribution of load along the tendon profile and in the inclined plane, the horizontal component can be determined at any point $x$ by:

$$q_{sh} = q_x \cos \beta$$

where $\beta$ is the angle of inclination of the tendon profile (Fig. 3).

With the web acting as a beam fixed at the top and bottom flanges, the distribution of the lateral load, $q_{sh}$, to the bottom and top flanges can be determined as (refer to Fig. 6a):

$$q_{shf} = q_{sh}(b^2d^3)(3a + b)$$

$$q_{sff} = q_{sh}(a^2d^3)(a + 3b)$$

where

$q_{shf}$ = load imparted to the bottom flange at any point $x$

$q_{sff}$ = load imparted to the top flange at any point $x$

$d$ = dimension between center lines of flanges

$m$ = dimension between chord of tendon profile and centerline of top flange

Other terms are as depicted in Fig. 6.

In Eqs. (15) and (16) above, the author has assumed full fixity of the web to the flanges. The reader should be aware that the actual distribution of load imparted to the flanges in a particular case will be a function of the relative stiffness of the web and flanges. It should also be emphasized that these secondary transverse forces also cause flexural and shear stresses in the webs and flanges.

**HORIZONTALLY CURVED GIRDER**

The effect of horizontal curvature with respect to friction has been previously discussed and a method of evaluation has been presented in Eq. (4). The previous discussion considered the transverse force distribution into the flanges resulting from longitudinal prestressing in a laterally inclined plane. In a horizontally curved girder an additional transverse force is introduced by virtue of the radial forces generated by the horizontal curvature of the prestressing tendons.

Tendon radial load, $q_r$, resulting from the tendon force, $T$, is given as:

$$q_r = T/R_h$$

where $R_h$ is the horizontal radius of curvature. At any point $x$ along the tendon pro-
file, measured from the jacking end, the radial force $q_{sa}$ is determined as:

$$q_{sa} = T_i/R_h$$  \hspace{1cm} (18)

where $T_i$ is determined from Eq. (4).

The local effect of $q_{sa}$ in the web and the possibility of tendon pullout from the web has been previously reported. Distribution of $q_{sa}$ to the bottom and top flanges can be determined in the same manner as that of the $q_{sh}$ forces [see Fig. 6 and Eqs. (15) and (16)] such that:

$$q_{ref} = q_{sa} (b^2/d^2)(3a + b)$$  \hspace{1cm} (19)

$$q_{ref} = q_{sa} (a^2/d^2)(a + 3b)$$  \hspace{1cm} (20)

Because the $q_{sa}$ forces are directed inward with respect to horizontal curvature, the force from the outside web (with respect to curvature) will produce compression in the flanges thus reducing the $q_{sh}$ forces produced by tendon plane inclination. However, the force from the inside web (with respect to curvature) will produce tension in the flanges and will thus be additive to the $q_{sh}$ forces from tendon plane inclination.

It, therefore, appears that equilibrium of lateral forces in the flanges is unbalanced. How the radial forces from both webs are distributed throughout the transverse width of the flanges is unclear and could be the subject of a research testing program. A conservative approach is to provide transverse reinforcement in the flanges to accommodate the tensile force induced by the inside web.

**NUMERICAL EXAMPLES**

To illustrate the proposed design procedure, two numerical examples are presented, one for a simple span girder and the other for a continuous girder. Also, the special case of external tendons is covered.

**Simple Span Girder**

Consider first a simple span girder illustrated in Fig. 7(a).

Jacking is assumed from one end. The jacking force, $T_o$, is assumed at 4250 kips per web. For the purpose of evaluating the distribution of forces along the span length, the span is divided into sixteen equal segments of 10 ft. Galvanized rigid duct is assumed with $\mu = 0.25$ and $K = 0.0002$.

Let $f_e = 3.0$ ft.

From Eq. (1):
From Eq. (2):
\[ f_i = \frac{f}{\sin \beta} = 3.4642 \]

From Eq. (2):
\[ R_i = (4f_i^2 + c^2)/8f_i = 925.465 \]

where in this example the symbol \( c \) denotes the span length.

If friction in the tendons is ignored, the distribution \( q_i \) would be determined from Eqs. (10) and (8) as follows and as illustrated in Fig. 8(a):

\[ T_{sh} = T_o/[1 + 16(f/c^2)^{1/2}] = 4234 \text{ kips} \]
\[ q_i = 8T_{sh}/[c^4 + 16f_i(c - 2x)^2]^{1/2} = 4.584 \text{ kips per ft} \]

Considering friction, the evaluation of force at the quarter-span (Point 4) is conducted as follows:

The terms to be used in Eq. (3) are determined as:

\[ L = 40 \text{ ft} \]
\[ KL = 0.0002(40) = 0.008 \]
\[ \alpha = 0.0432 \]
\[ \mu = 0.25(0.0432) = 0.0108 \]
\[ KL + \mu = 0.008 + 0.0108 = 0.0188 < 0.3 \]

Therefore, Eq. (3b) is used to evaluate \( T_x \):

\[ T_x = T_o/(1 + KL + \mu \alpha) \]
\[ = 4250/1.0188 \]
\[ = 4171 \text{ kips} \]

From Eq. (12):
\[ q_{sh} = q_{sh} [c^4 + 16f_i(c - 2x)^2]^{1/2} \]
Substituting numerical values for \( x = 40, c = 160, f_i = 3.464, T_o = 4171 \):

\[ q_{sh} = 4.511 \text{ kips per ft} \]

From Eq. (14) with \( \beta = 60 \) deg:

\[ q_{sh} = q_{sh} \cos \beta = 4.511(0.5) = 2.256 \]

Referring to Figs. 6(a) and (7a) and Eq. (9), the following values are determined:

\[ m = 2.625, x = 40, y_i = 2.598, \]
\[ y_e = 2.25, b = 4.875, a = 1.4375. \]

The lateral force in the bottom flange is determined from Eq. (15) as:

\[ q_{sh} = q_{sh} (b^3/d^5)(3a + b) \]
\[ = 2.256(0.0945)(9.1875) \]
\[ = 1.959 \text{ kips per ft} \]
The lateral force in the top flange is determined from Eq. (16) as:

\[ q_{eff} = q_d \left( \frac{a^2 d^3}{2} \right)(a + 3b) \]

\[ = 2.256(0.0082)(16.0625) \]

\[ = 0.297 \text{ kips per ft} \]

In the same manner, values for all of the 1/16 points of the girder are determined and are plotted in Fig. 8.

If the tendons were to be jacked from both ends the distribution of \( q \) forces would be symmetrical about the midspan with the values determined for Points 0 to 8.

**Continuous Girder**

Using the same procedure illustrated above for the simple span girder, a two-span continuous girder [Fig. 7(b)] has been evaluated and the distribution of \( q \) forces are plotted in Fig. 9. As shown in Fig. 9, in the negative moment area at the interior support, compression is developed by the laterally inclined tendons in the flanges.

It should be noted that in the negative moment area where the tendon profile is concave downward, the evaluation of the
Fig. 8. Distribution of $q$ forces (simple span girder example).
Fig. 9. Distribution of $q$ forces (continuous girder example).
Fig. 10. Lateral forces at an external tendon deviation saddle.

term "m" used to determine the values of "a" and "b" in Eqs. (15) and (16) is as indicated in Fig. 6(b).

External Tendons

In this example, an external tendon is assumed with the configuration indicated in Fig. 10. The angle of inclination of the tendon profile plane, \( \beta \), is 20 deg. In the plane of the tendon profile, the angle of deviation of the tendon profile at the deviation saddle, \( \gamma \), is 16.16 deg. After allowance for friction, the tendon force, \( T_x \), at the deviation saddle was determined as 665 kips.

The reaction of the tendon profile in the inclined plane of the tendon profile, \( R_i \), is determined by the parallelogram law [Fig. 10(c)]. However, to determine the lateral load, the value of the vertical component of \( R_i \) in the plane of the tendon, must be determined as:
The lateral horizontal component, $R_{v_h}$, is then:

$$R_{v_h} = R_v \cos \beta$$

$$= 185(0.93969)$$

$$= 173.84 \text{ kips}$$

The tension force in the bottom flange is then determined from Fig. 10(e) and Eq. (15) as:

$$Q_{vbf} = R_{vbf} \frac{b^2}{d^2}(3a + b)$$

$$= 173.84(0.11087)(8.778)$$

$$= 169 \text{ kips}$$

Assuming an 8 in. flange thickness, the flange stress at the toe of the deviation saddle is:
If a 5500 psi concrete with a strength at stressing of 4000 psi is assumed, the respective theoretical cracking stresses are 556 and 474 psi, respectively.

**INFLUENCE OF LATERAL INCLINATION OF TENDON PROFILE**

The above examples were evaluated with a tendon profile lateral angle of inclination, $\beta$, equal to 60 deg in the first two cases and 20 deg in the last case. To determine the influence of this parameter, stresses were evaluated for the case of the simple span girder at midspan and at the end of the girder by varying the angle of inclination $\beta$. The plot shown in Fig. 11 indicates that there is an approximate 70 percent increase of lateral force (or stress) when the angle of inclination is decreased from 60 to 45 deg. Similarly, there is an approximate 195 percent increase in stress when the angle decreases from 60 to 30 deg.

Therefore, this plot verifies the obvious conclusion that the tension induced in the flanges increases from the one extreme case, where the stress is zero when the web is vertical (an angle of web inclination with respect to the horizontal of 90 deg) to a maximum as the angle of inclination approaches a horizontal condition.

This indicates, as would be expected, that at midspan, because of the close proximity of the tendon profile to the bottom flange, the stress in the bottom flange is of a larger magnitude than that for the top flange. At the ends of the girder, because of the proximity of the tendon profile to the top flange, the stress is of a larger magnitude in the top flange than the bottom flange.

Usually, in current practice, the angle of inclination of tendon profiles is at or near 60 deg. The author is aware of two projects in the United States where in one case the angle of inclination is 40 deg and in the other case 20 deg. In both cases external tendons are used.

**DESIGN RECOMMENDATIONS**

1. At the very least, the forces developed by draped longitudinal tendons embedded in inclined webs should be evaluated for those designs where the angle of inclination is outside the limits of the current state of the art, i.e., angles of inclination of approximately 45 deg or less. Certainly, the condition at deviation saddles for external tendons should be investigated.

2. From the limited study conducted in this paper it appears that the effect of friction on the lateral forces is not a significant factor. Therefore, for simplification of the transverse cross section analysis, friction may be ignored on the conservative side.

3. Secondary moments and shears in the flanges and webs resulting from the forces induced by laterally inclined longitudinal post-tensioning, which may be of significance, have not been evaluated in this paper. However, a method of evaluating the lateral force induced by inclined post-tensioning tendons has been presented. Once these forces are determined they can be included with other loads in the conventional frame analysis of the cross section.

4. Obviously, where secondary stresses produced by laterally inclined longitudinal post-tensioning become excessive in themselves or in conjunction with other stresses, the amount and distribution of transverse reinforcing steel and/or transverse pretensioning will require evaluation.

**CONCLUSION**

Longitudinal post-tensioning in a laterally inclined plane will produce lateral forces in the flanges of box girders. The magnitude of these lateral forces is a function of the following parameters: (1) prestress force, (2) tendon profile and (3) angle of inclination of the tendon profile plane.

For the case of draped tendons within inclined webs, the maximum tensile force in the bottom flange is located at the low point of the tendon profile, decreasing toward the end of the girder or a tendon inflection point.
Maximum tensile force in the top flange is at either end of the girder or a tendon inflection point. In the case of external tendons, it is obvious that the maximum tensile force will occur in the bottom flange at the location of the deviation saddle and will be of a larger magnitude (concentrated force) than for the embeded draped tendon (distributed force).

Depending upon the parameters mentioned above, the magnitude of lateral stress induced in the flanges are, in general, negligible when taken alone. The possible exception may be for the case of external tendons. However, when these stresses are superimposed on other primary stresses (dead and live load, torsion, thermal gradient, etc.) and other secondary transverse stresses that may have been considered (or ignored) it may be that the tensile capacity of the concrete will be exceeded resulting in cracking.

Or, if other potential cracking mechanisms are present (see Ref. 5) they may be aggravated to a point where cracking is triggered. At least one reference in the literature has reported the observation that lateral forces produced by laterally inclined longitudinal tendons can be wholly or partially attributed to cracking in some bridges.

It should be noted that the evaluation of lateral forces presented in this paper have been based upon the assumption of full fixity of the web to the flanges, the actual distribution of load imparted to the flanges will be a function of the relative stiffness of the web and flanges. Further, this evaluation has not considered the effects of anchorage seating, overstressing and subsequent release-back, presence of diaphragms, and time-dependent losses.
REFERENCES


APPENDIX—NOTATION

\[
\begin{align*}
\alpha &= \text{dimension from cable profile to center of bottom flange} \\
b &= \text{dimension from cable profile to center of top flange} \\
c &= \text{chord length of tendon (cable) profile curve} \\
c' &= c - 2x = \text{chord length at point } x \\
d &= \text{dimension between centerlines of flanges} \\
e &= \text{base of Naperian logarithms} \\
f &= \text{flange stress at the toe of deviation saddle (external tendons)} \\
f' &= \text{cable offset with respect to coordinates } x \text{ and } y \\
f_i &= \text{sag of tendon profile in its inclined plane} \\
f_v &= \text{vertical sag of tendon profile} \\
m &= \text{dimension between chord of tendon profile and center line of top flange} \\
q &= \text{uniformly distributed load} \\
q_h &= \text{distributed lateral force induced in web along tendon profile} \\
q_r &= \text{distributed load in plane of tendon profile} \\
q_r &= \text{horizontally curved tendon radial load} \\
q_{rs} &= \text{horizontally curved tendon radial load at any point } x \\
q_{rsbf} &= \text{distribution of } q_{rs} \text{ to bottom flange} \\
q_{ref} &= \text{distribution of } q_{rs} \text{ to top flange} \\
q_v &= \text{distributed vertical load induced in web} \\
q_x &= \text{distributed load at point } x \\
q_{ebf} &= \text{load imparted to the bottom flange at any point } x \\
q_{eh} &= \text{horizontal component of distributed load in tendon plane} \\
q_{en} &= \text{distributed load in plane of tendon profile at point } x \\
q_{ef} &= \text{load imparted to top flange at any point } x \\
y &= \text{ordinate of cable curve} \\
y_i &= \text{dimension from tendon to its chord in inclined plane} \\
y_e &= \text{dimension from tendon to its chord in vertical plane} \\
H &= \text{horizontal component of cable tension} \\
K &= \text{friction wobble coefficient per foot of prestressing tendon} \\
K' &= \mu\alpha' = \text{modification factor considering effect of horizontal curvature of friction} \\
L &= \text{length of prestressing steel element from jack to point } x \\
M &= \text{bending moment} \\
M_x &= \text{bending moment at point } x \\
Q_e &= \text{tension force in bottom flange (external tendons)} \\
R_h &= \text{horizontal radius of curvature of tendon} \\
R_i &= \text{tendon radius of curvature in inclined plane} \\
R_i &= \text{reaction of tendon profile in inclined plane of tendon profile (external tendons)} \\
R_e &= \text{vertical component of } R_i \text{ (external tendons)}
\end{align*}
\]
Metric (SI) Conversion Factors

1 ft = 0.305 m
1 in. = 25.4 mm
1 kip = 4.5 kN
1 kip per ft = 14.75 kN/m
1 psi = 0.006895 MPa

\[ R_{oh} = \text{horizontal component of } R_e \text{ (external tendons)} \]
\[ T = \text{cable (tendon) tension} \]
\[ T_p = \text{steel stress or force at jacking end} \]
\[ T_x = \text{steel stress or force at any point } x \]
\[ T_x = \text{cable tension at point } x \]
\[ T_{sh} = \text{horizontal component of cable tension at point } x \]
\[ \alpha = \text{total angular change of prestressing steel profile (in its laterally inclined plane) in radians from jacking end to point } x \]
\[ \alpha' = \text{horizontal angle change in radians per foot} \]
\[ \beta = \text{angle of inclination of tendon profile with respect to horizontal axis} \]
\[ \gamma = \text{angle of deviation of tendon profile in its plane at deviation saddle (external tendons)} \]
\[ \theta = \text{angle between tension in cable, } T, \text{ and horizontal component, } H \]
\[ \mu = \text{friction curvature coefficient} \]

NOTE: Discussion of this paper is invited. Please submit your comments to PCI Headquarters by September 1, 1986.