Appendix XI
Detailing Requirements of the Prestressed Concrete Girder Bridge

1.a. Transverse Reinforcement in potential plastic hinge zones using the implicit shear detailing approach.

\[ A_{bh} = \text{cross sectional area of the spiral reinforcement} = 0.31\text{ in}^2 \ (\#5\text{ rebar}) \]
\[ s = \text{center-to-center spacing of the spiral reinforcement} = 120\text{ mm} \]
\[ D^* = \text{the out-to-out diameter of the spiral reinforcement in the circular section} = 921\text{ mm} \]
\[ \rho_{provided} = \frac{2A_{bh}}{sD} = \frac{2(0.31\text{in}^2)(25.4\text{mm})^2}{(120\text{mm})(921\text{mm})} = 0.00362 \quad \text{[Recommended, 2001]} \]

\[ K_{\text{shape}} = \text{factor that depends on the shape of the section} = 0.32 \text{ for a circular section} \]
\[ \Lambda = \text{fixity factor} = 2 \text{ for fixed-fixed} \]
\[ \rho_t = \text{ratio of longitudinal reinforcement} \]
\[ = \frac{A_t}{A_g} \]
\[ = \frac{(18)(1.56\text{in}^2)(25.4\text{mm})^2}{894,167\text{mm}^2} \]
\[ = 0.0203 \]
\[ \phi = \text{resistance factor for seismic shear} = 0.85 \]
\[ f_{su} = \text{the ultimate tensile stress of the longitudinal reinforcement. If } f_{su} \text{ is not available from coupon tests, the it shall be assumed that } f_{su} = 1.5 \ f_y. \]
\[ A_g = \text{gross area of the column} = 0.25\pi(1067\text{mm})^2 = 894,000\text{mm}^2 \]
\( A_{cc} = \text{area of column core concrete, measured to the centerline of the perimeter hoop or spiral} = 0.25\pi(937\text{mm} - 16\text{mm})^2 = 666,000 \text{mm}^2 \)

\( D' = \text{diameter of the column concrete core (center-to-center of the rebars)} = 867 \text{ mm} \)

\( L = \text{column length} = 5432 \text{ mm} \)

\[ \tan \alpha = \frac{D'}{L} = \frac{867 \text{mm}}{5432 \text{mm}} = 0.160 \]

\( \rho_v = \text{provided} \rho_v = 0.00362 \)

\( A_v = 0.8A_g \) for a circular column

\[ \tan \theta = \left( \frac{1.6 \rho_v A_v}{\Lambda \rho_{v} A_g} \right)^{0.25} = \left( \frac{1.6 \times 0.00362}{2 \times 0.0203} \right)^{0.25} = 0.581 \]

\( \tan \theta > \tan \alpha \rightarrow O.K. \)

\[ \rho_{v, \text{required}} = K_{\text{shape}} \frac{A_g}{\phi} \frac{f_{sw}}{f_{yh}} A_{cc} \tan \alpha \tan \theta \]

\[ = (0.32)(2) \left( \frac{0.0203}{0.85} \right)(1.5) \left( \frac{894,000 \text{mm}^2}{666,000 \text{mm}^2} \right) \left( \frac{867 \text{mm}}{5432 \text{mm}} \right)(0.581) \quad [\text{Recommended, 2001}] \]

\[ = 0.00285 \]

\( \rho_v \text{ provided} > \rho_{v, \text{required}} \text{ (Good)} \)

1.b. Transverse Reinforcement outside the Plastic Hinge Zones

\( \rho_{v}^* = \text{transverse reinforcement ratio outside the plastic hinge zone} \)

\( \rho_{v}^* \text{ provided} = 0.00362 \)

\( \rho_v = \text{the steel provided in the potential plastic hinge zone} = \rho_{v}^* \text{ provided} = 0.00362 \)

\[ \rho_{v, \text{required}}^* = \rho_v - 0.17 \frac{f_c}{f_{yh}} = 0.00362 - 0.17 \frac{25}{420} = 0.00160 \]

\( \rho_{v}^* \text{ provided} > \rho_{v, \text{required}}^* \text{ (Good)} \)

[Recommended, 2001]
2.a. Transverse Reinforcement in potential plastic hinge zones using the explicit shear detailing approach.

\[ \phi V_s \geq V_u - \phi(V_p + V_c) \]

\[ V_p = \frac{\Lambda}{2} P_e \tan \alpha \]

\[ = \frac{2}{2} (2,880,000 N \left( \frac{867 \text{mm}}{5432 \text{mm}} \right) \]

\[ = 460,000 N \]

Inside the plastic hinge zone:

\[ V_c = 0.05 \sqrt{f_c A_c} \]

\[ = 0.05 \sqrt{25 (0.8) (894,000 \text{mm}^2)} \]

\[ = 179,000 N \]

\[ A_{bh} = 200 \text{mm}^2 \]

\[ S = 120 \text{mm} \]

\[ f_{sh} = 420 N / \text{mm}^2 \]

\[ D'' = 937 \text{mm} - 16 \text{mm} = 921 \text{mm} \]

\[ \tan \theta = \left( \frac{1.6(0.00362)(0.8)}{2(0.0203)} \right)^{0.25} = 0.581 \]

\[ \tan \alpha = \frac{867 \text{mm}}{5432 \text{mm}} = 0.160 \]

\[ \tan \theta > \tan \alpha \]

\[ \theta = 30.166^\circ > 25^\circ \]

\[ V_s = \frac{\pi}{2} \frac{A_{bh}}{s} f_{sh} D'' \cot \theta \]

\[ = \frac{\pi}{2} \left( \frac{200 \text{mm}^2}{120 \text{mm}} \right) (420 N / \text{mm}^2) (921 \text{mm}) \left( \frac{1}{0.581} \right) \]

\[ = 1,740,000 N \]

\[ V_u = 52,200 N \]

\[ \phi V_s = 0.85 (1,740,000 N) = 1,480,000 N \]

\[ V_u - \phi(V_p + V_c) = 52,200 N - 0.85 (460,000 N + 179,000 N) = -491,000 N \]

\[ \phi V_s > V_u - \phi(V_p + V_c) \]

Thus the transverse (shear) reinforcement is adequate (Good).
2.b. Transverse Reinforcement outside the plastic hinge zones using the explicit shear detailing approach.

Outside the plastic hinge zone:

\[ V_c = 0.17 \sqrt{f'_c A_e} \]
\[ = 608,000 N \]
\[ V_u - \phi(V_p + V_c) = 52,200 N - 0.85(460,000 N + 608,000 N) = -855,600 N \]
\[ \phi V_s > V_u - \phi(V_p + V_c) \]

[Recommended, 2001]

Thus the transverse (shear) reinforcement is adequate (Good).

3. Transverse Reinforcement for Confinement at Plastic Hinges

\( \rho_s \) = transverse reinforcement for confinement at plastic hinges

\( U_{sf} \) = strain energy capacity (modulus of toughness) of the transverse reinforcement

\[ = 110 \text{ MPa} \]
\[ = 110 \text{ N/mm}^2 \]

\( P_c \) = factored axial load (N) including seismic effects

\[ = 2,890,000 \text{ N (from Appendix VIII)} \]

\[ \rho_{s, provided} = \frac{4A_{sh}}{D^w s} = 2(0.00362) = 0.00724 \]

\[ \rho_{s, required} = 0.008 \frac{f'_c}{U_{sf}} \left[ 12 \left( \frac{P_c}{f'_c A_g} + \rho_t \frac{f_s}{f'_c} \right)^2 \left( \frac{A_g}{A_{cc}} \right)^2 - 1 \right] \]
\[ = 0.008 \frac{25}{110} \left[ 12 \left( \frac{2,890,000}{(25)(894,000)} + 0.0203 \frac{420}{25} \right)^2 \left( \frac{894,000}{666,000} \right)^2 - 1 \right] \]
\[ = 0.00687 \]

[Recommended, 2001]

\( \rho_s \) provided > \( \rho_s \) required (Good)
4. Spiral Spacing for Confinement at Plastic Hinges

Required Spacing \( s = 100 \text{ mm} \)
Provided Spacing \( s = 120 \text{ mm} \)

**Provided Spacing > Required Spacing (Not Good)**

[Recommended, 2001]

5. Transverse Spiral Reinforcement at the Moment Resisting Connection between Members (Column/Beam and Column/Footing Joints)

\( \rho_s \) provided = 0.00724 (from 2.a.)

\[
\tan \alpha = \frac{D}{H_c}
\]

\( D = \) diameter of the column framing into the joint = 1067 mm
\( H_c = \) the height of the cap beam / joint = 1676 mm

\( \rho_s \) required = transverse spiral reinforcement at the moment resisting connection between members (column/beam and column/footing joints)

\( \rho_s \) required = the maximum of \( \rho_s \) required obtained in 2.a. (\( \rho_s \) required = 0.00687) and the following formula:

\[
\rho_{s,\text{required}} = 0.76 \frac{\rho_s}{\phi} \frac{f_{\text{su}}}{f_{\text{yh}}} \frac{A_r}{A_{c\ell}} \tan^2 \alpha
\]

\[
= 0.76 \left( \frac{0.0203}{0.85} \right) (1.5) \left( \frac{894,000 \text{mm}^2}{666,000 \text{mm}^2} \right) \left( \frac{1067 \text{mm}}{1676 \text{mm}} \right)^2
\]

\[
= 0.01481
\]

Thus \( \rho_s \) required obtained using the above formula (\( \rho_s \) required = 0.01481) controls.

\( \rho_s \) **provided = 0.00724 < \rho_s \) **required = 0.01481 (Not Good).**

[Recommended, 2001]
6. Stirrups in the Pier Cap Beam

Required stirrups $A_{jv} = 0.16 A_{st}$, located within a distance 0.5D from the column face, where:

$A_{jv} = \text{total provided stirrups cross sectional area in the pier cap beam}$

$A_{st} = \text{total area of longitudinal steel in the column}$

$D = \text{diameter of the column.}$

$0.5 D = 0.5 (1067 \text{ mm}) = 533.5 \text{ mm.}$

$0.16 A_{jv} = 0.16 (18 \text{ in}^2) (\frac{25.4 \text{ mm}}{\text{lin}})^2 = 2,899 \text{ mm}^2$

For all five columns, there are 32-#5 stirrups within 0.5D of the column. Therefore,

$A_{jv} = (32)(0.31 \text{ in}^2) (\frac{25.4 \text{ mm}}{\text{lin}})^2 = 6400 \text{ mm}^2$

[Recommended, 2001]

Provided stirrups $A_{jv} = 6400 \text{ mm}^2 > \text{Required stirrups} = 2,899 \text{ mm}^2$ (Good)

The total construction cost for the bridge is given in Table XI-1. General conditions, overhead, profit and contingencies were not included in the total cost, because the estimate was only intended to be used to illustrate how much approximately the new LRFD Guidelines were going to impact the construction cost. The calculation to estimate the additional cost incurred in order to comply with the new LRFD Guidelines is as follows.

**Additional Spiral Reinforcing Steel Calculation**

The requirement for transverse spiral reinforcement at the moment resisting connection between members (column/beam and column/footing joints) controls, because its required spiral reinforcement ratio ($\rho_s = 0.01481$) is the highest. For practical reasons, that reinforcement ratio will be used for the whole length of the column instead of just at the connections between the columns, pier cap beam and footings. The spiral spacing will
also be reduced from 120 mm to 100 mm, as required for confinement at plastic hinges. Thus now the minimum required cross sectional area of the spiral reinforcing bar can be found by using the formula for the provided \( \rho_s \):

\[
\rho_{s, \text{provided}} = \frac{4A_{bh}}{D''s}
\]

\[
0.01481 = \frac{4A_{bh}}{(921\text{mm})(100\text{mm})}
\]

\[
A_{bh} = \frac{(0.01481)(921\text{mm})(100\text{mm})}{4}
\]

\[
A_{bh} = 341\text{mm}^2
\]

\[
A_{bh} = 0.529\text{in.}^2
\]

The required cross sectional area is 0.529 in.\(^2\), and the smallest sufficient rebar size is rebar #7, which has a cross sectional area of 0.60 in.\(^2\), or 387 mm\(^2\).

Length covered by the spiral reinforcement = 5432 mm + 540 mm + 540 mm = 6512 mm
Table XI-1. The estimate for the construction cost of the prestressed concrete girder bridge. All prices are in US dollars. Virginia sales tax (4.5%) was applied to material price only. “From Means Heavy Construction Cost Data 2003. Copyright R.S. Means Co., Inc., Kingston, MA 781-585-7880; All rights reserved.”

<table>
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<tr>
<th>Item</th>
<th>Quantity</th>
<th>Units</th>
<th>Material Unit Price</th>
<th>Labor Unit Price</th>
<th>Equipment Unit Price</th>
<th>Total Unit Price</th>
<th>Subtotal Cost</th>
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<td>Concrete, Class 25 (25 MPa)</td>
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<td>Pier Cap Beam Formwork</td>
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<td>Column Formwork</td>
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<td>Reinforcing Steel in Place Epoxy Coated</td>
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<td>Steel Piles HP 310 x 79</td>
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<td>Aluminum Railing</td>
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<td>Pedestrian Fence</td>
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<td><strong>Total Cost</strong></td>
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<td><strong>1,139,941</strong></td>
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</tbody>
</table>
Spiral Diameter = 937 mm – 16 mm
    = 921 mm

#5 rebars at spacing s = 120 mm (as written on the drawings)

The length of one full turn

$$= \sqrt{(921\pi)^2 + 120^2}$$

$$= 2896\text{mm}$$

The number of turns

$$= \frac{6512\text{mm}}{120\text{mm}}$$

$$= 54.3$$

Total length of the spiral reinforcing bar for one column

$$= 2896\text{mm} \times 54.3$$

$$= 157,253\text{mm}$$

Total volume of the spiral reinforcing bar for one column

$$= \frac{1}{4} \pi (16\text{mm})^2 (157,253\text{mm})$$

$$= 31,617,592\text{mm}^3$$

Total volume of the spiral reinforcing bar for the whole pier (five columns)

$$= 5 \times 31,617,592\text{mm}^3$$

$$= 158,087,958\text{mm}^3$$

$$\approx 0.158\text{m}^3$$

Total weight of the spiral reinforcing bar for the whole pier

$$= 0.158\text{m}^3 \times 7850 \frac{\text{kg}}{\text{m}^3}$$

$$= 1240\text{kg}$$
#7 rebars at spacing $s = 100$ mm (as required by the new LRFD Guidelines)

The length of one full turn
$$= \sqrt{(921 \pi)^2 + 100^2}$$
$$= 2895 mm$$

The number of turns
$$= \frac{6512 mm}{100 mm}$$
$$= 65.1$$

Total length of the spiral reinforcing bar for one column
$$= 2895 mm \times 65.1$$
$$= 188,465 mm$$

Total volume of the spiral reinforcing bar for one column
$$= (387 mm^2) (188,465 mm)$$
$$= 72,935,955 mm^3$$

Total volume of the spiral reinforcing bar for the whole pier (five columns)
$$= 5 \times 72,935,955 mm^3$$
$$= 364,679,775 mm^3$$
$$\approx 0.365 m^3$$

Total weight of the spiral reinforcing bar for the whole pier
$$= 0.365 m^3 \times 7850 \frac{kg}{m^3}$$
$$= 2865 kg$$

Additional rebar that has to be placed in the pier
$$= 2865 kg - 1240 kg$$
$$= 1625 kg$$
According to the construction drawings, all the rebars in the pier are epoxy-coated. Therefore according to Table XI-1, the cost of placing 1625 kg additional rebar in the bridge pier is

\[ = 1625\text{kg} \times \frac{1.52\text{dollars}}{1\text{kg}} \]

\[ = 2,470\text{dollars} \]

The total construction cost was approximately $1,139,941. Thus the percentage of construction cost increase for compliance with the new LRFD Guidelines is

\[ = \frac{2,470\text{dollars}}{1,139,941\text{dollars}} \times 100\% \]

\[ \approx 0.2\% \]