Transverse Stiffener Requirements in Straight and Horizontally Curved Steel I-Girders

Yoon Duk Kim, Se-Kwon Jung and Donald W. White

Georgia Institute of Technology
School of Civil and Environmental Engineering
Atlanta, GA

2005 AASHTO Bridge Committee Agenda Item 38

June 27, 2005
Problem Statement

- Identify the demands on transverse stiffeners in curved and straight I-girders designed within the AASHTO (2004) limits:
  - Transversely-stiffened I-girders with
    - \( d_o/D \leq 3 \)
    - \( D/t_w \leq 150 \)
  - Longitudinally-stiffened I-girders with
    - \( d_o/D \leq 1.5 \)
    - \( D/t_w \leq 300 \)
FEA Parametric Studies, Test Configuration

\[ P_2 = 3P \]
\[ P_1 = P \]
\[ R_1 = P \]
\[ R_2 = 3P \]
\[ d_0 = L_b/2 \]

\[ L_b \]

\[ P \]
\[ 2P \]

\[ P L_b \]
Parametric Studies (Transversely-Stiffened I-Girders)

- $D = 96 \text{ in (8 ft)}$
- $d_o/D = 0.5, 1, 2 & 3$
- Straight & Curved with $R = \max(10d_o, 100 \text{ ft})$
- $D/t_w = 150$ (other $D/t_w$ values considered for flat webs)
- $F_{yw} = F_{ys} = 70 \text{ ksi}$ (other $F_y$ values considered for flat webs)
- $F_{yf} = 100 \text{ ksi}$ (other $F_y$ values considered for flat webs)
- $b_f/2t_f = 6.47$ (compact limit), except $b_f/2t_f = 5$ for $d_o/D = 3$
- $b_f$ determined such that $M_u \sim 0.75M_n$ based on the one-third rule
- $b_t/t_p = 10$ in primary studies (other $b_t/t_p$ considered in supplementary studies)
- Various one- and two-sided stiffener sizes
Parametric Studies (Longitudinally-Stiffened I-Girders)

- \( D = 96 \text{ in (8 ft)} \)
- \( d_o/D = 0.5, 1 & 1.5 \)
- Straight & Curved with \( R = \max(10d_o, 100 \text{ ft}) \)
- \( D/t_w = 300 \) (other \( D/t_w \) values considered for flat webs)
- \( F_{yw} = F_{ys} = 70 \text{ ksi} \) (other \( F_y \) values considered for flat webs)
- \( F_{yf} = 100 \text{ ksi} \) (other \( F_y \) values considered for flat webs)
- \( b_f/t_f = 6.47 \) (compact limit)
- \( b_f \) determined such that \( M_u \sim 0.75M_n \) based on the one-third rule
- \( b_t/t_p = 10 \) in primary studies (other \( b_t/t_p \) considered in supplementary studies)
- Various one- and two-sided stiffener sizes
- Longitudinal stiffener not included in models
TFA Strength vs $I_t/I_{tcr}$

$d_o/D = 1$, $D/t_w = 150$

$V_{\text{max}} / V_{\text{n (AASHTO)}}$

$I_{tA1}/I_{tcr} = 18.5$

$I_{tR}/I_{tcr} = 20.0$

$I_{t} = A_s^2 (b_t/t_p)/3n$

$I_t/I_{tcr} = I_t$ req’d to develop $V_n = V_{cr}$
TFA Strength vs $I_t/l_{tcr}$

$d_o/D = 1$, $D/t_w = 150$

AASHTO (2004) area requirement, one-sided stiffeners

AASHTO (2004) area requirement, two-sided stiffeners

Recommended

$I_{A2}/l_{tcr} = 0$

$I_{A1}/l_{tcr} = 18.5$

$I_{R}/l_{tcr} = 20.0$

$V_{max}/V_{n(AASHTO)}$ vs $l_t/l_{tcr}$

- Straight girders with one-sided stiffeners
- Curved girders with one-sided stiffeners
- Straight girders with two-sided stiffeners
- Curved girders with two-sided stiffeners
Shell Model - Perspective View of Deformed Geometry at Max Load

\[ l_t = l_{tcr}, \frac{d_o}{D} = 1, \frac{D}{t_w} = 150, \text{1-sided stiffener} \]

Undeformed geometry

Deformed geometry

(Scale Factor = 5.0)

Straight I-girder (note: \(18.5l_{tcr}\) is req’d to satisfy the AASHTO (2004) area reqmt)
Shell Model – Mid-thickness Von Mises Stress Distribution at Max Load

\( l_t = l_{tcr}, \quad d_o/D = 1, \quad D/t_w = 150, \) 1-sided stiffener

(Scale Factor = 5.0)

Straight I-girder (note: 18.5\( l_{tcr} \) is req’d to satisfy the AASHTO (2004) area reqmt)
Perspective View of Deformed Geometry at Max Load

$l_t = 6l_{t_{cr}}, \frac{d_o}{D} = 1, D/t_w = 150, 1\text{-sided stiffener}$

(Scale Factor $= 5.0$)
Curved I-girder
Mid-thickness Von Mises Stress Distribution at Max Load

$l_t = 6l_{tcr}$, $d_o/D = 1$, $D/t_w = 150$, 1-sided stiffener

(Scale Factor = 5.0)

Curved I-girder
TFA Strength vs $I_t/I_{tcr}$

$d_o/D = 1$, $D/t_w = 300$
“... the important panel influence on the stiffener is lateral loading induced by panel buckling. For panels bounded by actual flange members there is evidence of a significant tension field loading on the stiffener, but the effect of this, even for the more slender plates considered, is less than the beneficial effect resulting from the lateral stiffener bending restraint provided by the flange. This indicates that bending rigidity rather than axial stiffness is the most important parameter for the design of the stiffener, which supports the emphasis placed on stiffener rigidity in the study by Horne and Grayson.”
Similar conclusions have been reached by

- Rahal and Harding (1990b & 1991)
- Horne and Grayson (1983)
- Xie (2000)
- Lee, Yoo and Dong (2002 & 2003)
Required Stiffener Sizes, $d_o/D = 1$, one-sided stiffeners

$$D/t_w = 1.12 \left( \frac{E_k}{F_{yw}} \right)^{0.5} \quad t_w = D \left( \frac{F_{yw}}{E/k} \right)^{0.5} / 1.12 \quad I_{tcr} = bt_w^3$$

$$b'_{tcr(C=1)} = \left[ 3 \left( \frac{b_t}{t_p} \right) I_{tcr}/n \right]^{0.25}$$
Required Stiffener Sizes, $d_o/D = 1$, one-sided stiffeners

\[ \frac{b_t}{b'_{tcr(C=1)}} \]  

- $b_t/b'_{tcr(C=1)}$ (AASHTO 2004)
- $b_t/b'_{tcr(C=1)}$ (Horne & Grayson 1983)
- $b_t/b'_{tcr(C=1)}$ (Stanway et al. 1996)
- $b_t/b'_{tcr(C=1)}$ FEA, this study

$D/t_w = 1.12 \sqrt{E_k/F_{yw}}$
Required stiffener sizes, $d_o/D = 1$, two-sided stiffeners

$\frac{b_t}{b_{t_{cr(C=1)}}}$ (AASHTO 2004)
$\frac{b_t}{b_{t_{cr(C=1)}}}$ (Horne & Grayson 1983)
$\frac{b_t}{b_{t_{cr(C=1)}}}$ (Stanway et al. 1996)
$\frac{b_t}{b_{t_{cr(C=1)}}}$ FEA, this study
$b_t = b_{t_{cr(C=1)}}$, $D/t_w = 1.12 \sqrt{E_k/F_{yw}}$

Recommended
6.10.11.1.2 Projecting Width

The width, $b_t$, of each projecting stiffener element shall satisfy:

$$b_t \geq 2.0 + \frac{D}{30}$$  \hspace{1cm} (6.10.11.1.2-1)

and

$$16t_p \geq b_t \geq b_f / 4$$  \hspace{1cm} (6.10.11.1.2-2)

where:

$b_f$ = for I-sections, full width of the widest compression flange within the field section under consideration; for tub girder sections, full width of the widest top flange within the field section under consideration; for closed box sections, the limit of $b_f/4$ does not apply (in.)

$t_p$ = thickness of the projecting stiffener element (in.)
6.10.11.1.3 Moment of Inertia

For transverse stiffeners adjacent to web panels in which \( V_u \leq \phi V_{cr} \) in both panels, the moment of inertia of the transverse stiffener shall satisfy the smaller of the following limits:

\[
I_t \geq b t_w^3 J \quad \text{(6.10.11.1.3-1)}
\]

\[
I_t \geq \frac{D^4 \rho_t^{1.3}}{40} \left( \frac{F_{yw}}{E} \right)^{1.5} \quad \text{(6.10.11.1.3-2)}
\]

where:

\[
b = \text{the smaller of } d_o \text{ and } D \text{ (in.)}
\]

\[
d_o = \text{the smaller of the adjacent web panel widths (in.)}
\]

\[
I_t = \text{moment of inertia of the transverse stiffener taken about the edge in contact with the web for single stiffeners and about the mid-thickness of the web for stiffener pairs (in.}^4\text{)}
\]
\[ J = \text{stiffener bending rigidity constant} \]

\[
= \frac{2.5}{(d_o / D)^2} - 2.0 \geq 0.5 \quad (6.10.11.1.3-3)
\]

\[ V_{cr} = \text{shear-buckling resistance defined by Eq. 6.10.9.2-1 (kip)} \]

\[ V_u = \text{shear in the web at the section under consideration due to factored loads (kip)} \]

\[ \phi_v = \text{resistance factor for shear specified in Article 6.5.4.2} \]

\[ \rho_t = \text{the larger of } F_{yw}/F_{crs} \text{ and } 1.0 \]

\[ F_{crs} = \text{local buckling stress for the stiffener (ksi)} \]

\[
= \frac{0.31E}{\left(\frac{b_t}{t_p}\right)^2} \leq F_{ys} \quad (6.10.11.1.3-4)
\]

\[ F_{ys} = \text{specified minimum yield strength of the stiffener (ksi)} \]
For transverse stiffeners adjacent to web panels in which $V_u > \phi_v V_{cr}$ in one or both panels, the moment of inertia of the transverse stiffeners shall satisfy Eq. 2.

(to develop the buckling strength of a flat web panel, no TFA)

\[ I_t \geq d_o t_w^3 J \]
\[ b = \min(d_o, D) \]
\[ J = \frac{2.5}{\left(\frac{d_o}{D}\right)^2} - 2 \leq 0.5 \]
\[ I_t = \frac{t_p b_t^3}{3} \quad \text{one – sided stiffeners} \]
\[ I_t = 2 \frac{t_p b_t^3}{3} \quad \text{two – sided stiffeners} \]
Required J to Develop the *Buckling* Strength (Flat Webs, no TFA)

\[ u_{cr} = \left( \frac{V_{cr}(l_t = \infty) - V_{cr}(l_t = 0)}{V_{cr}(l_t = 0)} \right) \]

\begin{align*}
\Delta & \text{ Stanway et al. (1993), } \mu_{cr} = 0.95 \\
\square & \text{ Stanway et al. (1993), } \mu_{cr} = 0.90 \\
\lozenge & \text{ Stanway et al. (1993), } \mu_{cr} = 0.80 \\
\text{AASHTO (2004)} & \\
\text{Bleich (1952)} & \\
\text{Timoshenko and Gere (1961)} &
\end{align*}
Behavior of Equations, Plate Stiffeners

... more than 1,200 parametric cases considered
(see spreadsheet)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Eq (2-2) D = 4 ft</td>
<td>Eq (3-1) Eq (4-1)</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>50</td>
<td>2</td>
<td>10</td>
<td>1</td>
<td>150</td>
<td>0.125</td>
<td>0.046 0.079</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>50</td>
<td>3</td>
<td>10</td>
<td>1</td>
<td>150</td>
<td>0.083</td>
<td>0.046 0.079</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>50</td>
<td>4</td>
<td>10</td>
<td>1</td>
<td>150</td>
<td>0.063</td>
<td>0.046 0.079</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>50</td>
<td>5</td>
<td>10</td>
<td>1</td>
<td>150</td>
<td>0.050</td>
<td>0.046 0.079</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>50</td>
<td>6</td>
<td>10</td>
<td>1</td>
<td>150</td>
<td>0.042</td>
<td>0.046 0.079</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>50</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>150</td>
<td>0.125</td>
<td>0.039 0.056</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>50</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>150</td>
<td>0.083</td>
<td>0.039 0.056</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>50</td>
<td>4</td>
<td>5</td>
<td>1</td>
<td>150</td>
<td>0.063</td>
<td>0.039 0.056</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>50</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>150</td>
<td>0.050</td>
<td>0.039 0.056</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>50</td>
<td>6</td>
<td>5</td>
<td>1</td>
<td>150</td>
<td>0.042</td>
<td>0.039 0.056</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>50</td>
<td>2</td>
<td>16</td>
<td>1</td>
<td>150</td>
<td>0.125</td>
<td>0.052 0.120</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>50</td>
<td>3</td>
<td>16</td>
<td>1</td>
<td>150</td>
<td>0.083</td>
<td>0.052 0.120</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>50</td>
<td>4</td>
<td>16</td>
<td>1</td>
<td>150</td>
<td>0.063</td>
<td>0.052 0.120</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>50</td>
<td>5</td>
<td>16</td>
<td>1</td>
<td>150</td>
<td>0.050</td>
<td>0.052 0.120</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>50</td>
<td>6</td>
<td>16</td>
<td>1</td>
<td>150</td>
<td>0.042</td>
<td>0.052 0.120</td>
</tr>
</tbody>
</table>
Summary

- For 1-sided plate stiffeners, the recommended $I_t$ eqs give comparable or slightly smaller stiffener sizes vs the AASHTO (2004) area reqmt, except in the “dip” where the area reqmt does not govern.

- The recommended $I_t$ eqs result in approx equal girder strengths regardless of whether the stiffeners are 1- or 2-sided.
Summary

- The recommended eqs are independent of the applied shear $V_u$
  - Simpler, avoid dependency of shear resistance on $V_u$
  - The $V_u/\phi_v V_n$ term in the AASHTO (2004) area reqmt causes the actual $V_n$ to be smaller than the computed $V_n$
  - Fortunately, Eqs. (2-1) and (2-2) govern the stiffener size in a number of practical cases + one size is often selected for all the stiffeners in practice

- Eq. (3-2) facilitates the calculation of a single size for all transverse stiffeners, since it is also independent of $D/t_w$ and $d_o/D$

- Eq. (3-1) gives a constant $I_t$ reqmt for $d_o/D \geq 1$
Thank You for your Attention

I’d be happy to address any questions
Additional Slides
Required stiffener sizes, $d_o/D = 3$, one-sided stiffeners ($F_{yw} = 70$ ksi, $b_t/t_p = 10$)

$$b_s/b'_{scr(C=1)}$$

Recommended
Required stiffener sizes, $d_o/D = 2$, one-sided stiffeners ($F_{yw} = 70$ ksi, $b_t/t_p = 10$)

Recommended

$D/t_w = 1.12 \sqrt{E_k/F_{yw}}$
Required stiffener sizes, $d_o/D = 1.5$, one-sided stiffeners ($F_{yw} = 70$ ksi, $b_t/t_p = 10$)

\[ b_s/b'_{scr(C=1)} \quad \text{(AASHTO 2004)} \]
\[ b_s/b'_{scr(C=1)} \quad \text{(Horne & Grayson 1983)} \]
\[ b_s/b'_{scr(C=1)} \quad \text{(Stanway et al. 1996)} \]
\[ b_s/b'_{scr(C=1)} \quad \text{FEA, this study} \]

\[ b_s = b'_{scr(C=1)}, \quad D/t_w = 1.12\sqrt{E_k/F_{yw}} \]
Required stiffener sizes, $d_o/D = 0.5$, one-sided stiffeners ($F_{yw} = 70$ ksi, $b_t/t_p = 10$)

\[ b_s / b_{scr(C=1)} \]

Recommended

- $b_s / b_{scr(C=1)}$ (AASHTO 2004)
- $b_s / b_{scr(C=1)}$ (Horne & Grayson 1983)
- $b_s / b_{scr(C=1)}$ (Stanway et al. 1996)
- $b_s / b_{scr(C=1)}$ FEA, this study
- $b_s = b_{scr(C=1)}$, $D/t_w = 1.12 \sqrt{Ek/F_{yw}}$
Relative frequency polygon vs the normal distribution, $V_{test}/V_n$

122 Experimental Shear Strength tests (White & Barker 2004)