Who We Are, at FHWA

A USDOT Agency responsible for ensuring that America’s roads and highways continue to be the safest and most technologically up-to-date.

We provide financial (> $30 Billion/year) and technical support to States and Local Governments.
Effect of Federal Aid on Transportation Structures

Federal Aid has been increasing significantly ($14,257,907,017 in ISTEA To $23,365,688,795 in TEA21), but deficiencies remain significant.
FHWA’s Top Priorities

✓ Make transportation safer, more reliable and secure,

✓ Reduce traffic congestion, and

✓ Minimize impact on the environment
1-Develop and Deploy Reliable and Safer Specifications, and increase the Design and Service Life

- Safer
- Reduce congestion
- Minimize impact on the environment
Evolution Of Design Specifications

1931 - First AASHO Specs
   Evolved into AASHTO Standard Specs (SLD, and LFD), and became a patch document with inconsistencies and gaps

1994 - Load and Resistance Factor Design (LRFD)

1998 - 2nd Edition of LRFD

2004 - 3rd Edition of LRFD
AASHTO OC LRFD Survey
April 2004

For updates and inquiries, contact:
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(202)-366-4598 Direct
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Service Load DESIGN

Nominal Load Effect, $Q_n \leq \frac{R_n}{FS}$

Service Load Design (SLD):

$$(f_t)_D + (f_t)_L \leq 0.55F_y\text{, or}$$

$$1.82(f_t)_D + 1.82(f_t)_L \leq F_y$$
LFD Design Equation

$$\Sigma \gamma_i Q_i \leq \phi R_n$$

where:

- $\gamma_i = \text{Load factor}$
- $\gamma_i Q_i = \text{Factored load, required capacity}$
- $\phi = \text{Resistance factor}$
- $\phi R_n = \text{Capacity}$

Load Factor Design (LFD):

1.3\[1.0(f_t)_D + 5/3(f_t)_L\] \leq \phi F_y \text{, or}

1.3(f_t)_D + 2.17(f_t)_L \leq \phi F_y \quad (\phi \text{ by judgment})
Design & Service Life for The Standard Specifications

Design Life is 50 years

Service Life could be less than 50
Innovative LRFD Design Specifications

- Longer Design Life (75 years)
- Allows use of High Performance Material; Service Life (>75 years)
- Consistent Reliability and Safety Factors for all bridges,
- More Realistic Live Load Model, and Distribution Factors
- State of the Art Provisions and Design Procedures
Basic LRFD Design Equation

$$\Sigma \eta_i \gamma_i Q_i \leq \phi R_n = R_r$$

where:

- $\eta_i$ = Load modifier
- $\gamma_i$ = Load factor
- $Q_i$ = Nominal force effect
- $\phi$ = Resistance factor
- $R_n$ = Nominal resistance
- $R_r$ = Factored resistance = $\phi R_n$

Sample LRFD Design Equation:

$$1.25(f_v)_D + 1.75(f_v)_L \leq \phi F_y$$  
($\phi$ by calibration)
(new live-load model)
LRFD = More Accurate Live Load Model, HL-93

- **Design Truck:**

- **Design Tandem:**
  Pair of 25.0 KIP axles spaced 4.0 FT apart
  superimposed on

- **Design Lane Load** 0.64 KLF uniformly distributed load

---

U.S. Department of Transportation
Federal Highway Administration
<table>
<thead>
<tr>
<th>SUPPORTING COMPONENTS</th>
<th>TYPE OF DECK</th>
<th>TYPICAL CROSS-SECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel Beam</td>
<td>Cast-in-place concrete slab, precast concrete slab, steel grid, glued/spiked panels, stressed wood</td>
<td>(a)</td>
</tr>
<tr>
<td>Closed Steel or Precast Concrete Boxes</td>
<td>Cast-in-place concrete slab</td>
<td>(b)</td>
</tr>
<tr>
<td>Open Steel or Precast Concrete Boxes</td>
<td>Cast-in-place concrete slab, precast concrete deck slab</td>
<td>(c)</td>
</tr>
<tr>
<td>Cast-in-Place Concrete Multicell Box</td>
<td>Monolithic concrete</td>
<td>(d)</td>
</tr>
<tr>
<td>Cast-in-Place Concrete Tee Beam</td>
<td>Monolithic concrete</td>
<td>(e)</td>
</tr>
<tr>
<td>Precast Solid, Voided or Cellular Concrete Boxes with Shear Keys</td>
<td>Cast-in-place concrete overlay</td>
<td>(f)</td>
</tr>
<tr>
<td>Precast Solid, Voided, or Cellular Concrete Box with Shear Keys and with or without Transverse Posttensioning</td>
<td>Integral concrete</td>
<td>(g)</td>
</tr>
</tbody>
</table>

LRFD = More Accurate Live-Load Distribution Factors
### Sample Live-Load Distribution Factors

**Moments – Interior Beams**

**Table 4.6.2.2b-1 Distribution of Live Loads Per Lane for Moment in Interior Beams.**

<table>
<thead>
<tr>
<th>Type of Beams</th>
<th>Applicable Cross-Section from Table 4.6.2.2.1-1</th>
<th>Distribution Factors</th>
<th>Range of Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Deck, Filled Grid, Partly Filled Grid, or Unfilled</td>
<td>a, e, k and also i, j if sufficiently connected</td>
<td></td>
<td>3.5 ≤ S ≤ 16.0</td>
</tr>
<tr>
<td>Grid Deck Composite with Reinforced Concrete Slab on Steel</td>
<td></td>
<td></td>
<td>20 ≤ L ≤ 240</td>
</tr>
<tr>
<td>or Concrete Beams; Concrete T-Beams, T- and Double T-Sections</td>
<td></td>
<td></td>
<td>4.5 ≤ t_s ≤ 12.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>One Design LaneLoaded:</td>
<td>N_b ≥ 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.06 + ( \left( \frac{S}{14} \right)^{0.4} \left( \frac{S}{L} \right)^{0.3} \left( \frac{K_g}{12.0 L t_s^3} \right)^{0.1} )</td>
<td>10,000 ≤ K_g ≤ 7,000,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Two or More Design Lanes Loaded:</td>
<td>N_b = 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.075 + ( \left( \frac{S}{9.5} \right)^{0.6} \left( \frac{S}{L} \right)^{0.2} \left( \frac{K_g}{12.0 L t_s^3} \right)^{0.1} )</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**

1) Units are in LANES and not WHEELS

2) No multiple presence factor applied (tabulated equations)
LRFD Calibration is Scientific

& based on performance of prior design specs & existing bridge inventory

First use

Time-tested satisfactory performance

Failure

Design Requirement

Time
Reliability and Calibration of Standard & LRFD Specifications

\[ \beta = \frac{\bar{R} - \bar{Q}}{\sqrt{\sigma_R^2 + \sigma_Q^2}} \]

Normally Distributed \( Q \) and \( R \):

Lognormally Distributed \( Q \) and \( R \):

\[ \beta = \frac{\ln\left(\frac{\bar{R}}{\bar{Q}}\right)}{\sqrt{V_R^2 + V_Q^2}} \]
States’ Experience with the AASHTO LRFD Design Specifications

(>2,240 LRFD Bridges – 2004)
Doremus Avenue Viaduct
(Newark, NJ)
Rt. 9, Nacote Creek Bridge (South Jersey)
Barclay Creek Bridge Site

- Environmentally sensitive area
- 170 foot span required for hydraulic requirements

- HPS 70W LRFD Bridge
- 174 foot span length

- Overall, a good experience
WSDOT Spliced I-Girders
Twisp River Bridge, Twisp, WA

Single-span spliced concrete girders spanning 195 ft

2002 PCI Award
FLDOT
St. George Island Bridge Apalachicola, FL

✓ 21,542’ long bridge
✓ Post-tensioned bulb-tee girders
FLDOT
Hathaway Bridge, Panama City, FL

✓ 3,815’ long
✓ 330’ typical span
Segmental boxes
Long Span Bridges in LRFD?
(Great River Bridge, Desha County, AR)

682 ft - 1,520 ft – 682 ft Cable-Stay Bridge
Long Span Bridges in LRFD? (Hoover Dam Bypass Project)

Composite Concrete Deck Arch Bridge (~2,000 ft)
Some State DOT's Conclusion

✓ New Jersey: “.. major step forward ..”
  “.. cost savings of up to 8 percent ..”
✓ Washington: “.. good experience … was not so difficult..”
  “.. comprehensive .... powerful ..”
✓ Florida: “.. good experience … was not so difficult..”
  “.. comprehensive .... powerful ..”
SUMMARY
LRFD

- Comprehensive, rational, and powerful specs
- Result in safer and more reliable transportation structures
- Design Life is 75 years
THANK YOU

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LRFD
Loads and Loads Distribution

Firas I. Sheikh Ibrahim, Ph.D., P.E.
Federal Highway Administration
Washington, DC
Basic LRFD Design Equation

\[ \sum \eta_i \gamma_i Q_i \leq \phi R_n = R_r \quad \text{Eq. (1.3.2.1-1)} \]

where:

- \( \eta_i \) = \( \eta_D \eta_R \eta_I \)
- \( \gamma_i \) = Load factor
- \( \phi \) = Resistance factor
- \( Q_i \) = Nominal force effect
- \( R_n \) = Nominal resistance
- \( R_r \) = Factored resistance = \( \phi R_n \)
### Load Combinations and Load Factors

<table>
<thead>
<tr>
<th>Load Combination</th>
<th>DC</th>
<th>DD</th>
<th>LL</th>
<th>IM</th>
<th>WA</th>
<th>WS</th>
<th>WL</th>
<th>FR</th>
<th>TU</th>
<th>CR</th>
<th>SH</th>
<th>TG</th>
<th>SE</th>
<th>Use One of These at a Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>EQ</td>
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<td><strong>Limit State</strong></td>
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<tr>
<td><strong>STRENGTH-I</strong></td>
<td>( \gamma_p ) 1.75</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>0.50/1.20</td>
<td>( \gamma_{TG} )</td>
<td>( \gamma_{SE} )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>STRENGTH-II</strong></td>
<td>( \gamma_p ) 1.35</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>0.50/1.20</td>
<td>( \gamma_{TG} )</td>
<td>( \gamma_{SE} )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td><strong>STRENGTH-III</strong></td>
<td>( \gamma_p ) -</td>
<td>1.00</td>
<td>1.40</td>
<td>-</td>
<td>1.00</td>
<td>0.50/1.20</td>
<td>( \gamma_{TG} )</td>
<td>( \gamma_{SE} )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>STRENGTH-IV</strong></td>
<td>( \gamma_p ) 1.5</td>
<td>-</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>0.50/1.20</td>
<td>-</td>
<td>-</td>
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<td>-</td>
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<td></td>
</tr>
<tr>
<td><strong>EH, EV, ES, DW</strong></td>
<td><strong>DC ONLY</strong></td>
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<td></td>
</tr>
<tr>
<td><strong>STRENGTH-V</strong></td>
<td>( \gamma_p ) 1.35</td>
<td>1.00</td>
<td>0.40</td>
<td>1.00</td>
<td>1.00</td>
<td>0.50/1.20</td>
<td>( \gamma_{TG} )</td>
<td>( \gamma_{SE} )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>EXTREME-I</strong></td>
<td>( \gamma_p ) ( \gamma_{EQ} )</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>EXTREME-II</strong></td>
<td>( \gamma_p ) 0.50</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>SERVICE-I</strong></td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.30</td>
<td>0.30</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00/1.20</td>
<td>( \gamma_{TG} )</td>
<td>( \gamma_{SE} )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>SERVICE-II</strong></td>
<td>1.00</td>
<td>1.30</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00/1.20</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>SERVICE-III</strong></td>
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<td>0.80</td>
<td>1.00</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00/1.20</td>
<td>( \gamma_{TG} )</td>
<td>( \gamma_{SE} )</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>FATIGUE-LL, IM &amp; CE</strong></td>
<td><strong>ONLY</strong></td>
<td>-</td>
<td>0.75</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tbody>
</table>
### Load Factors for Permanent Loads, $\gamma_p$

<table>
<thead>
<tr>
<th>Type of Load</th>
<th>Load Factor</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC: Component and Attachments</td>
<td>1.25</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>DD: Downdrag</td>
<td>1.80</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>DW: Wearing Surfaces and Utilities</td>
<td>1.50</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>EH: Horizontal Earth Pressure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Active</td>
<td>1.50</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>• At-Rest</td>
<td>1.35</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>EV: Vertical Earth Pressure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Overall Stability</td>
<td>1.35</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>• Retaining</td>
<td>1.35</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>Structure</td>
<td>1.30</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>• Rigid Buried</td>
<td>1.35</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>Structure</td>
<td>1.35</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td>• Rigid Frames</td>
<td>1.95</td>
<td>0.90</td>
<td></td>
</tr>
</tbody>
</table>
Basic LRFD Design Live Load
HL-93 -- (Article 3.6.1.2.1)

✦ Design Truck: ⇒

⇒ Design Tandem:
Pair of 25.0 KIP axles spaced 4.0 FT apart

or

Superimposed on

✦ Design Lane Load 0.64 KLF
uniformly distributed load
For negative moment (between points of permanent-load contraflexure) & interior-pier reactions, check an additional load case:
LRFD Fatigue Load
(Article 3.6.1.4.1)

- Design Truck only =>
  - w/ fixed 30-ft rear-axle spacing
  - Placed in a single lane
Section 4

Structural Analysis and Evaluation

4.6 Static Analysis

4.6.2 Approximate Methods of Analysis

4.6.2.2 Beam-Slab Bridges

↓

Live-Load Lateral Distribution Factors
### Table 4.6.2.1-1 Common Deck Superstructures Covered in Articles 4.6.2.2 and 4.6.2.2.3.

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<th>TYPE OF DECK</th>
<th>TYPICAL CROSS-SECTION</th>
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<tr>
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<td>(d)</td>
</tr>
<tr>
<td>Cast-in-Place Concrete Tee Beam</td>
<td>Monolithic concrete</td>
<td>(e)</td>
</tr>
<tr>
<td>Precast Solid, Voided or Cellular</td>
<td>Cast-in-place concrete overlay</td>
<td>(f)</td>
</tr>
<tr>
<td>Concrete Boxes with Shear Keys</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precast Solid, Voided, or Cellular</td>
<td>Integral concrete</td>
<td>(g)</td>
</tr>
<tr>
<td>Concrete Box with Shear Keys and</td>
<td></td>
<td></td>
</tr>
<tr>
<td>with or without Transverse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Posttensioning</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Live-Load Distribution Factors

## Moments – Interior Beams

Table 4.6.2.2.2b-1 Distribution of Live Loads Per Lane for Moment in Interior Beams.

<table>
<thead>
<tr>
<th>Type of Beams</th>
<th>Applicable Cross-Section from Table 4.6.2.2.1-1</th>
<th>Distribution Factors</th>
<th>Range of Applicability</th>
</tr>
</thead>
</table>
| Concrete Deck, Filled Grid, Partially Filled Grid, or Unfilled Grid Deck Composite with Reinforced Concrete Slab on Steel or Concrete Beams; Concrete T-Beams, T- and Double T-Sections | a, e, k and also i, j if sufficiently connected to act as a unit | One Design Lane Loaded:  
0.06 + \( \left( \frac{S}{14} \right)^{0.4} \left( \frac{S}{L} \right)^{0.3} \left( \frac{K_g}{12.0Lt_s^3} \right)^{0.1} \)  
Two or More Design Lanes Loaded:  
0.075 + \( \left( \frac{S}{9.5} \right)^{0.6} \left( \frac{S}{L} \right)^{0.2} \left( \frac{K_g}{12.0Lt_s^3} \right)^{0.1} \) | 3.5 \( \leq S \leq 16.0 \)  
20 \( \leq L \leq 240 \)  
4.5 \( \leq t_s \leq 12.0 \)  
\( N_b \geq 4 \)  
10,000 \( \leq K_g \leq 7,000,000 \)  
\( N_b = 3 \) |

**Notes:**

1) Units are in LANES and not WHEELS!

2) **No multiple presence factor** applied (tabulated equations)

3) **May be Different** for Positive and Negative Flexure Locations!
## Live-Load Distribution Factors

### Shear – Interior Beams

Table 4.6.2.2.3a-1 Distribution of Live Load per Lane for Shear in Interior Beams.

<table>
<thead>
<tr>
<th>Type of Superstructure</th>
<th>Applicable Cross-Section from Table 4.6.2.2.1-1</th>
<th>One Design Lane Loaded</th>
<th>Two or More Design Lanes Loaded</th>
<th>Range of Applicability</th>
</tr>
</thead>
</table>
| Concrete Deck, Filled Grid, Partially Filled Grid, or Unfilled Grid Deck Composite with Reinforced Concrete Slab on Steel or Concrete Beams; Concrete T-Beams, T-and Double T-Sections | a, e, k and also i, j if sufficiently connected to act as a unit | $0.36 + \frac{S}{25.0}$ | $0.2 + \frac{S}{12} - \left(\frac{S}{35}\right)^{2.0}$ | $3.5 \leq S \leq 16.0$  
$20 \leq L \leq 240$  
$4.5 \leq t_s \leq 12.0$  
$N_b \geq 4$ |

**Notes:** Same for Positive and Negative Flexure Locations!
### Live-Load Distribution Factors

**Moments – Exterior Beams**

Table 4.6.2.2d-1 Distribution of Live Loads Per Lane for Moment in Exterior Longitudinal Beams.

<table>
<thead>
<tr>
<th>Type of Superstructure</th>
<th>Applicable Cross-Section from Table 4.6.2.2.1-1</th>
<th>One Design Lane Loaded</th>
<th>Two or More Design Lanes Loaded</th>
<th>Range of Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Deck, Filled Grid, Partially Filled Grid, or Unfilled Grid Deck Composite with Reinforced Concrete Slab on Steel or Concrete Beams; Concrete T-Beams, T- and Double T-Sections</td>
<td>a, c, k and also i, j if sufficiently connected to act as a unit</td>
<td>Lever Rule</td>
<td>Sample equation: $g = e g_{interior}$ $e = 0.77 + \frac{d_e}{9.1}$</td>
<td>$-1.0 \leq d_e \leq 5.5$</td>
</tr>
</tbody>
</table>

**Notes:** distribution factor for the exterior beam shall not be taken to be less than that which would be obtained by assuming that the cross-section deflects and rotates as a rigid cross-section (SPECIAL ANALYSIS).

$$ R = \frac{N_L}{N_b} + \frac{X_{ext} \sum^{N_L} e}{\sum^{N_b} X^2} $$
## Live-Load Distribution Factors

### Shear – Exterior Beams

Table 4.6.2.3b-1 Distribution of Live Load per Lane for Shear in Exterior Beams.

<table>
<thead>
<tr>
<th>Type of Superstructure</th>
<th>Applicable Cross-Section from Table 4.6.2.2.1-1</th>
<th>One Design Lane Loaded</th>
<th>Two or More Design Lanes Loaded</th>
<th>Range of Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Deck, Filled Grid, Partially Filled Grid, or Unfilled Grid Deck Composite with Reinforced Concrete Slab on Steel or Concrete Beams: Concrete T-</td>
<td>a, e, k and also i, j if sufficiently connected to act as a unit</td>
<td>Lever Rule</td>
<td>( g = e \ g_{\text{interior}} ) ( e = 0.6 + \frac{d_e}{10} )</td>
<td>(-1.0 \leq d_e \leq 5.5)</td>
</tr>
</tbody>
</table>

**Notes:** distribution factor for the exterior beam shall not be taken to be less than that which would be obtained by assuming that the cross-section deflects and rotates as a rigid cross-section (SPECIAL ANALYSIS)

\[
R = \frac{N_L}{N_b} + \frac{X_{\text{ext}} \sum N_L e}{\sum N_b x^2}
\]
Live-Load Distribution Factors
Exterior Girder – *Lever Rule*

\[ = R \times \frac{a}{s} \]
Live-Load Distribution Factors
Exterior Girder - Special Analysis

\[ R = \frac{N_L}{N_b} + \frac{X_{\text{ext}} \sum_{N_L} e}{\sum_{N_b} x^2} \quad \text{Eq. (C4.6.2.2.2d-1)} \]

- \( R \): reaction on exterior beam in terms of lanes
- \( N_L \): number of loaded lanes under consideration
- \( e \): eccentricity of a lane from the center of gravity of the pattern of girders (ft)
- \( x \): horizontal distance from the center of gravity of the pattern of girders to each girder (ft)
- \( X_{\text{ext}} \): horizontal distance from the center of gravity of the pattern of girders to the exterior girder (ft)
- \( N_b \): number of beams or girders
QUESTIONS?
Unified Straight and Curved Steel Girder Design Specifications
Introduction
Unified Steel Specifications

Straight
Curved
One Specs!
Fundamentals

✓ Primary-Strength Flexural & Shear Effects
✓ Lateral Flange Effects
  ✓ Differential Deflection Effects
  ✓ Torsion Effects
  ✓ Lateral Force Effects
  ✓ Second-Order Effects
✓ Cross Frame Forces
FLB and LTB

Anchor point 1

Anchor point 2

$F_{nc} = C_b \left[ 1 - \left( 1 - \frac{F_{yr}}{R_h F_{yc}} \right) \left( \frac{L_b - L_p}{L_r - L_p} \right) \right] R_b R_h F_{yc} \leq R_b R_h F_{yc}$

$F_{nc} = \left[ 1 - \left( 1 - \frac{F_{yr}}{R_h F_{yc}} \right) \left( \frac{\lambda_f - \lambda_{pf}}{\lambda_{rf} - \lambda_{pf}} \right) \right] R_b R_h F_{yc}$

$F_{nc} = \frac{C_b R_b \pi^2 E}{b} \leq R_b R_h F_{yc}$

$C_b R_b \pi^2 E \left( \frac{L_b}{r_t} \right)^2$
Post Web Buckling Strength

\[
\frac{f_{bu}}{R_b R_h} \leq \phi_f F_{yf} \Rightarrow f_{bu} \leq \phi_f R_b R_h F_{yf}
\]

Buckled Web Sheds Stress to the
Compression Flange Reducing
Flange Yielding Moment

\[
R_b = \frac{\text{Moment First Yield with Buckled Web}}{M_y = F_y S} \leq 1.0
\]

\[
R_b = 1 - \left( \frac{a_{wc}}{1200 + 300 a_{wc}} \right) \left( \frac{2D_c}{t_w} - \lambda_{rw} \right) \leq 1.0
\]
Fundamentals

- Primary Flexural & Shear Effects
- Lateral Flange Effects
  - Differential Deflection Effects
  - Torsion Effects
  - Lateral Force Effects
  - Second-Order Effects
- Cross Frame Forces
Fundamentals

- Primary Flexural & Shear Effects
- Lateral Flange Effects
- Differential Deflection Effects
- Torsion Effects
- Lateral Force Effects
- Second-Order Effects
- Cross Frame Forces
Differential Load/Deflection Effects

• Outside girder carries more load
• Vertical Deflection is not equal between adjacent girders

=> **Torsional Effects on Girders, Lateral Flange Bending, and Affects fit-up during construction**
Fundamentals

✓ Primary Flexural & Shear Effects
✓ Lateral Flange Effects
  ✓ Differential Deflection Effects
✓ Torsion Effects
✓ Lateral Force Effects
✓ Second-Order Effects
✓ Cross Frame Forces
Torsion Effects

✓ Deformations

✓ Stresses
Torsion Deformations

✓ Twisting

✓ Warping

=> Affect fit-up during construction
Torsion Stresses

- St. Venant
- Warping

Normal Stresses

\[ \sigma = \frac{M_x y}{I_x} \]

Shear Stresses

\[ \tau = \frac{V_y Q_x}{I_x} \]
Fundamentals

- Primary Flexural & Shear Effects
- Lateral Flange Effects
  - Differential Deflection Effects
  - Torsion Effects
- Lateral Force Effects
- Second-Order Effects
- Cross Frame Forces
Lateral Force Effects

\[ f_{bu} \pm ? f_{\ell} \leq F_r \]

- \( f_{bu} \): Bending stress due to vertical loads
- \( f_{\ell} \): Flange lateral bending stress due to wind, skew, or curvature
Lateral Force Effects & “One-Third” Rule

Bending stress due to vertical loads:

\[ f_{bu} \]

Flange lateral bending stress due to wind, skew, or curvature:

\[ f_{bu} + \frac{1}{3} f_{\ell} \leq \phi_f F_{nc} \]

\[ f_{bu} + \frac{1}{3} f_{\ell} \leq \phi_f F_{yt} \]
Implementation of “One-Third” Rule

\[ f_{bu} + \frac{1}{3} f_{\ell} \leq F_r \]  
Strength Limit State, Constructibility-Compression

\[ M_u + \frac{1}{3} f_{\ell} S_x \leq M_r \]  
Strength Limit State – Compact Straight

\[ f_{bu} + f_{\ell} \leq F_r \]  
Constructibility Yielding \( \frac{1}{3} \Rightarrow 1 \)

\[ f_{bu} + \frac{1}{2} f_{\ell} \leq F_r \]  
Service Limit State \( \frac{1}{3} \Rightarrow \frac{1}{2} \)

\[ f_{bu} \leq F_r \]  
ALL L.S., Continuously Braced Flanges, \( f_{\ell} = 0 \)
### Implementation of “One-Third” Rule

<table>
<thead>
<tr>
<th>Category</th>
<th>Expression</th>
<th>Limit State</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strength Limit State, Constructibility-Compression</strong></td>
<td>$f_{bu} + \frac{1}{3} f_\ell \leq F_r$</td>
<td></td>
</tr>
<tr>
<td><strong>Strength Limit State – Compact Straight</strong></td>
<td>$M_u + \frac{1}{3} f_\ell S_x \leq M_r$</td>
<td></td>
</tr>
<tr>
<td><strong>Constructibility Yielding</strong></td>
<td>$f_{bu} + f_\ell \leq F_r$</td>
<td>$\frac{1}{3} \Rightarrow 1$</td>
</tr>
<tr>
<td><strong>Service Limit State</strong></td>
<td>$f_{bu} + \frac{1}{2} f_\ell \leq F_r$</td>
<td>$\frac{1}{3} \Rightarrow \frac{1}{2}$</td>
</tr>
<tr>
<td><strong>ALL L.S., Continuously Braced Flanges, $f_\ell = 0$</strong></td>
<td>$f_{bu} \leq F_r$</td>
<td></td>
</tr>
</tbody>
</table>
Implementation of “One-Third” Rule

\[
\begin{align*}
 f_{bu} + \frac{1}{3} f_{\ell} & \leq F_r & \text{Strength Limit State, Constructibility-Compression} \\
 M_u + \frac{1}{3} f_{\ell} S_x & \leq M_r & \text{Strength Limit State – Compact Straight} \\
 f_{bu} + f_{\ell} & \leq F_r & \text{Constructibility Yielding} \quad \frac{1}{3} \Rightarrow 1 \\
 f_{bu} + \frac{1}{2} f_{\ell} & \leq F_r & \text{Service Limit State} \quad \frac{1}{3} \Rightarrow \frac{1}{2} \\
 f_{bu} & \leq F_r & \text{ALL L.S., Continuously Braced Flanges, } f_{\ell} = 0
\end{align*}
\]
### Implementation of “One-Third” Rule

<table>
<thead>
<tr>
<th>Discretely Braced Flanges</th>
<th>Continuously Braced Flanges</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{bu} + \frac{1}{3} f_{\ell} \leq F_r$</td>
<td>$f_{bu} \leq F_r$</td>
</tr>
<tr>
<td>$M_u + \frac{1}{3} f_{\ell} S_x \leq M_r$</td>
<td>ALL L.S., Continuously Braced Flanges, $f_{\ell} = 0$</td>
</tr>
<tr>
<td>$f_{bu} + f_{\ell} \leq F_r$</td>
<td></td>
</tr>
<tr>
<td>Constructibility Yielding $\frac{1}{3} \Rightarrow 1$</td>
<td></td>
</tr>
<tr>
<td>Service Limit State $\frac{1}{3} \Rightarrow \frac{1}{2}$</td>
<td></td>
</tr>
</tbody>
</table>
Implementation of “One-Third” Rule

\[ f_{bu} + \frac{1}{3} f_{\ell} \leq F_r \quad \text{Strength Limit State, Constructibility-Compression} \]

\[ M_u + \frac{1}{3} f_{\ell} S_x \leq M_r \quad \text{Strength Limit State – Compact Straight} \]

\[ f_{bu} + f_{\ell} \leq F_r \quad \text{Constructibility Yielding} \quad \frac{1}{3} \Rightarrow 1 \]

\[ f_{bu} + \frac{1}{2} f_{\ell} \leq F_r \quad \text{Service Limit State} \quad \frac{1}{3} \Rightarrow \frac{1}{2} \]

\[ f_{bu} \leq F_r \quad \text{ALL L.S., Continuously Braced Flanges, } f_{\ell} = 0 \]
Fundamentals

✓ Primary Flexural & Shear Effects
✓ Lateral Flange Effects
  ✓ Differential Deflection Effects
  ✓ Torsion Effects
  ✓ Lateral Force Effects
✓ Second-Order Effects
✓ Cross Frame Forces (Primary Members)
Second-Order Effects (Art. 6.10.1.6)

- If \( L_b > 1.2L_p \sqrt{\frac{C_b R_b}{f_{bu}/F_{yc}}} \)

Second-order compression-flange lateral bending stresses may be approximated by amplifying first-order value:

\[
f_\ell = \left( \frac{0.85}{1 - \frac{f_{bu}}{F_{cr}}} \right) f_{\ell 1} \geq f_{\ell 1}
\]

\[
F_{cr} = \frac{C_b R_b \pi^2 E}{\left( \frac{L_b}{r_t} \right)^2}
\]
Fundamentals

✓ Primary Flexural & Shear Effects
✓ Lateral Flange Effects
  ✓ Differential Deflection Effects
  ✓ Torsion Effects
✓ Lateral Force Effects
✓ Second-Order Effects
✓ Cross Frame Forces (*Primary Members*)
SUMMARY
Unified Steel Specifications

Straight
Curved
One Specs!
Enough Said!
Shear Design
Based on
Sectional Model/Modified Compression Field Theory
Traditional Shear Design Method

1 - Before Cracking

2 - After Cracking

\[ V_s = \frac{A_s f_y}{s} d \]
Modified Compression Theory

Diagonal Compression, Tension in Cracked Concrete

Variable Angle Truss Analogy

Modified compression field theory, $f_1 \neq 0$
5.8.3.3 Nominal Shear Resistance

\[ V_n = V_c + V_s + V_p \quad (5.8.3.3-1) \]

\[ V_n = 0.25 f'_c b_v d_v + V_p \quad (5.8.3.3-2) \]

where:

\[ V_c = 0.0316 \beta \sqrt{f'_c} b_v d_v \quad (5.8.3.3-3) \]

\[ \beta = \frac{f_1 \cot \theta}{\sqrt{f'_c}} \leq \text{limit} \]

\[ V_s = \frac{A_v f_y d_v (\cot \theta + \cot \alpha) \sin \alpha}{s} \quad (5.8.3.3-4) \]
Factors for Determining $\beta$ and $\theta$

($V_u$ and $\varepsilon_x$)

\[ V_u = \frac{V_u - \phi V_p}{\phi b_v d_v} \]  

(5.8.2.9-1)

\( b_v = \text{effective web width} \)

\( d_v = \text{effective shear depth}; \text{distance between the resultants of the tensile and compressive forces due to flexure} \geq \text{the greater of } 0.9 \text{ de or } 0.72h \)

\( \phi = \text{resistance factor for shear specified in Article 5.5.4.2} \)
Strain $\varepsilon_x$ in Tension Chord

If the section contains at least the minimum transverse reinforcement:

$$\varepsilon_x = \frac{\varepsilon_t + \varepsilon_c}{2}$$

$$\varepsilon_x = \left( \frac{M_u}{d_v} + 0.5N_u + 0.5(V_u - V_p) \cot \theta - A_{ps} f_{po} \right)$$

where:

$A_s, A_{ps} = \text{area of non-prestressed, and prestressing steel on the flexural tension side of the member}$
### 5.8.3.4 Determination of $\beta$ and $\theta$

**Table 5.8.3.4.2-1**

Values of $\theta$ and $\beta$ for Sections with Transverse Reinforcement

<table>
<thead>
<tr>
<th>$\frac{v_u}{f'_c}$</th>
<th>$\leq -0.20$</th>
<th>$\leq -0.10$</th>
<th>$\leq -0.05$</th>
<th>$\leq 0$</th>
<th>$\leq 0.125$</th>
<th>$\leq 0.25$</th>
<th>$\leq 0.50$</th>
<th>$\leq 0.75$</th>
<th>$\leq 1.00$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\leq 0.075$</td>
<td>22.3</td>
<td>20.4</td>
<td>21.0</td>
<td>21.8</td>
<td>24.3</td>
<td>26.6</td>
<td>30.5</td>
<td>33.7</td>
<td>36.4</td>
</tr>
<tr>
<td></td>
<td>6.32</td>
<td>4.75</td>
<td>4.10</td>
<td>3.75</td>
<td>3.24</td>
<td>2.94</td>
<td>2.59</td>
<td>2.38</td>
<td>2.23</td>
</tr>
<tr>
<td>$\leq 0.100$</td>
<td>18.1</td>
<td>20.4</td>
<td>21.4</td>
<td>22.5</td>
<td>24.9</td>
<td>27.1</td>
<td>30.8</td>
<td>34.0</td>
<td>36.7</td>
</tr>
<tr>
<td></td>
<td>3.79</td>
<td>3.38</td>
<td>3.24</td>
<td>3.14</td>
<td>2.91</td>
<td>2.75</td>
<td>2.50</td>
<td>2.32</td>
<td>2.18</td>
</tr>
<tr>
<td>$\leq 0.125$</td>
<td>19.9</td>
<td>21.9</td>
<td>22.8</td>
<td>23.7</td>
<td>25.9</td>
<td>27.9</td>
<td>31.4</td>
<td>34.4</td>
<td>37.0</td>
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<tr>
<td></td>
<td>3.18</td>
<td>2.99</td>
<td>2.94</td>
<td>2.87</td>
<td>2.74</td>
<td>2.62</td>
<td>2.42</td>
<td>2.26</td>
<td>2.13</td>
</tr>
<tr>
<td>$\leq 0.150$</td>
<td>21.6</td>
<td>23.3</td>
<td>24.2</td>
<td>25.0</td>
<td>26.9</td>
<td>28.8</td>
<td>32.1</td>
<td>34.9</td>
<td>37.3</td>
</tr>
<tr>
<td></td>
<td>3.88</td>
<td>2.79</td>
<td>2.78</td>
<td>2.72</td>
<td>2.60</td>
<td>2.52</td>
<td>2.42</td>
<td>2.26</td>
<td>2.13</td>
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<tr>
<td>$\leq 0.175$</td>
<td>23.2</td>
<td>24.7</td>
<td>25.5</td>
<td>26.2</td>
<td>28.0</td>
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<td>32.7</td>
<td>35.2</td>
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<td>2.73</td>
<td>2.66</td>
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<td>2.60</td>
<td>2.52</td>
<td>2.44</td>
<td>2.28</td>
<td>2.14</td>
<td>1.96</td>
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<tr>
<td>$\leq 0.200$</td>
<td>24.7</td>
<td>26.1</td>
<td>26.7</td>
<td>27.4</td>
<td>29.0</td>
<td>30.6</td>
<td>32.8</td>
<td>34.5</td>
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<td>2.63</td>
<td>2.59</td>
<td>2.52</td>
<td>2.51</td>
<td>2.43</td>
<td>2.37</td>
<td>2.14</td>
<td>1.94</td>
<td>1.79</td>
</tr>
<tr>
<td>$\leq 0.225$</td>
<td>26.1</td>
<td>27.3</td>
<td>27.9</td>
<td>28.5</td>
<td>30.0</td>
<td>30.8</td>
<td>32.3</td>
<td>34.0</td>
<td>35.7</td>
</tr>
<tr>
<td></td>
<td>2.53</td>
<td>2.45</td>
<td>2.42</td>
<td>2.40</td>
<td>2.34</td>
<td>2.14</td>
<td>1.86</td>
<td>1.73</td>
<td>1.64</td>
</tr>
<tr>
<td>$\leq 0.250$</td>
<td>27.5</td>
<td>28.6</td>
<td>29.1</td>
<td>29.7</td>
<td>30.6</td>
<td>31.3</td>
<td>32.8</td>
<td>34.3</td>
<td>35.8</td>
</tr>
<tr>
<td></td>
<td>2.39</td>
<td>2.39</td>
<td>2.33</td>
<td>2.33</td>
<td>2.12</td>
<td>1.93</td>
<td>1.70</td>
<td>1.58</td>
<td>1.50</td>
</tr>
</tbody>
</table>
Additional Longitudinal Reinforcement to Resist Shear

\[ A_s f_y + A_{ps} f_{ps} \geq \frac{M_u}{d_v \phi_f} + 0.5 \frac{N_u}{\phi_c} + \left( \frac{V_u}{\phi_v} - 0.5 V_s - V_p \right) \cot \theta \]  

(5.8.3.5-1)

Figure C5.8.3.5-2 Force Variation in Longitudinal Reinforcement Near Maximum Moment Locations.
Figure C5.8.3.4.2-5 Flow Chart for Shear Design of Section Containing at Least Minimum Transverse Reinforcement.
THANK YOU!
Strut-and-Tie Model
5.8 SHEAR AND TORSION

5.8.1 Design Procedures

5.8.1.2 Regions Near Discontinuities

Where the plane sections assumption of flexural theory is not valid, regions of members shall be designed for shear and torsion using the strut-and-tie model as specified in Article 5.6.3. The provisions of Article 5.13.2 shall apply.
**D & B - Regions**

- **D** = Disturbed Discontinuity
- **B** = Bending Beam

---

**Dapped Beam**

**Tee Beam**

- $b_f$
**Basic Concepts**

- Visualize flow of stresses and sketch a strut-tie model to transfer load to the supports, where:
  - Compressive forces are resisted by concrete “struts”
  - Tensile forces are resisted by steel “ties”
  - Struts and ties meet at “nodes”
- For best serviceability, the model should follow the elastic flow of forces
Examples of Good and Poor Strut-and-Tie Models

1. Shortest & stiffest path to supports
2. Minimum release of energy (min cracks)
STM Procedures

1. Visualize flow of stresses
2. Sketch an idealized strut-and-tie model
3. Select area of ties
4. Check nodal zone stresses
5. Check strength of struts
6. Provide adequate anchorage for ties
7. Provide crack control reinforcement

Figure C5.6.3.2-1
Strut-and-Tie Model for a Deep Beam
Strength Limit State for STM

\[ P_r = \phi P_n \]  \hspace{1cm} (5.6.3.2-1)

where:

- \( P_r \) = Factored resistance of strut or tie
- \( P_n \) = Nominal resistance of strut or tie
- \( \phi \) = Resistance factor for tension or compression (5.5.4.2)

For compression in strut-and-tie models: \( \ldots 0.70 \)
For compression in anchorage zones:
  - normal weight concrete \( \ldots 0.80 \)
  - lightweight concrete \( \ldots 0.65 \)
For tension in steel in anchorage zones \( \ldots 1.00 \)
For tension of reinforced concrete \( \ldots 0.90 \)
For tension of prestressed concrete \( \ldots 1.00 \)
5.6.3.3 Proportioning of Compressive Struts

5.6.3.3.1 Strength of Unreinforced Strut

\[ P_n = f_{cu} A_{cs} \]  
(5.6.3.3.1-1)

5.6.3.3.4 Reinforced Strut

\[ P_n = f_{cu} A_{cs} + f_y A_{ss} \]  
(5.6.3.3.4-1)

where:

\( f_{cu} = \text{limiting compressive stress as specified in Article 5.6.3.3.3} \)

\( A_{cs} = \text{effective cross-sectional area of strut as specified in Article 5.6.3.3.2} \)

\( A_{ss} = \text{area of reinforcement in the strut} \)
Factors Affecting Size of Strut

Width of the strut is affected by:

- Location and distribution of reinforcement (tie) and its anchorage
- Size and location of bearing
Figure 5.6.3.3.2-1
Influence of Anchorage Conditions on Effective Cross-Sectional Area of Strut

a) Strut anchored by reinforcement

b) Strut anchored by bearing and reinforcement

c) Strut anchored by bearing and strut
5.6.3.3.3 Limiting Compressive Stress in Strut

\[ f_{cu} = \frac{f_c'}{0.8 + 170\varepsilon_l} \leq 0.85 f_c' \quad (5.6.3.3.3-1) \]

\[ \varepsilon_l = \varepsilon_s + (\varepsilon_s + 0.002)\cot^2\alpha_s \quad (5.6.3.3.3-2) \]

where:

- \( f_c' \) = specified compressive strength
- \( \varepsilon_s \) = the tensile strain in the concrete in the direction of the tension tie
- \( \alpha_s \) = the smallest angle between the compressive strut and adjoining tension ties (°)
5.6.3.4.1 Strength of Tie

\[ P_n = f_y A_{st} + A_{ps} \left[ f_{pe} + f_y \right] \]  \hspace{1cm} (5.6.3.4.1-1)

where

- \( f_y \) = yield strength of mild steel longitudinal reinforcement
- \( A_{st} \) = total area of longitudinal mild steel reinforcement in the tie
- \( A_{ps} \) = area of prestressing steel
- \( f_{pe} \) = stress in prestressing steel due to prestress after losses

5.6.3.5 Proportioning of Node Regions

The concrete compressive stress in the node regions of the strut shall not exceed:

- For node regions bounded by compressive struts and bearing areas: \(0.85 \phi f'_c\)
- For node regions anchoring a one-direction tension tie: \(0.75 \phi f'_c\)
- For node regions anchoring tension ties in more than one direction: \(0.65 \phi f'_c\)

Figure C5.6.3.2-1
Strut-and-Tie Model for a Deep Beam
5.6.3.6 Crack Control Reinforcement

• Provide orthogonal grid of reinforcement near each face of D-Region
• Maximum Bar Spacing = 12 in.
• Ratio $A_s / A_g \geq 0.003$ in each of the orthogonal directions
• Crack control reinforcement, located within tie, maybe considered as part of tie
Questions?