1 LOAD-INDUCED FATIGUE

1.1 TRUCK AND LANE LOADS

1.1.1 DESIGN TRUCK

![Image of a truck with weights and spacing of axles]

**FIGURE 1** Weights and Spacing of Axles

35 kN  145 kN  145 kN
4.3 m  4.3 to 9.0 m

1.1.2 DESIGN TANDEM

- A pair of 110 kN axles spaced 1.2 m apart.
- Transverse wheel spacing of 1.8 m.

1.1.3 LANE LOAD

- Uniformly distributed longitudinally (per unit length of lane):
  \[ W = 9.3 \text{ kN/m} \]
- Uniformly distributed transversely over a 3.0 m width
  \[ w = \frac{9.3}{3.0} = 3.1 \text{ kN/m}^2 \]
- Dynamic allowance is not added to lane loads.

1.1.4 DYNAMIC LOAD ALLOWANCE (IM)

The following dynamic load allowance is added for truck and tandem loads, but not for lane loads:

- Fatigue and fracture limit states: 15% of design truck
- All other limit states: 33% of design truck

1.1.5 POSITION OF LANES AND TRUCKS

- Design lanes are 3.6 m wide.
- The wheels are placed no closer than 0.6 m from the edge of the lane and no farther than 1.2 m.
- The lanes are positioned across the bridge in a manner that maximizes moments, shears and reactions.
- All lanes are loaded with trucks side by side, one truck per lane.

![Diagram showing minimum wheel distance from lane edge]

**Figure 2** Minimum Wheel Distance from Lane Edge
1.1 TRUCK AND LANE LOADS

1.1.6 LIVE LOAD COMBINATIONS

- Truck load
- Tandem load
- Lane load
- Tandem plus lane load
- One design truck with variable axle spacing plus lane load
- Special live load combination between points of dead load contraflexure and interior piers

Figure 3 Maximum Load on Exterior Girder

Figure 4 Maximum Load on Interior Girder
1.2 TRUCK LOADS ON HIGHWAYS

1.2.1 AXLE CONFIGURATIONS (Snyder et al, 1985)

![Axle Configurations Diagram]


The trucks were grouped by single-unit trucks, tractor-semitrailer trucks and tractor-semitrailer-trailer combinations.

Three biggest groups:
- 15,802 (57.4%) 3S-2 tractor-semitrailer trucks
- 3,337 (12.0%) 2-single-unit trucks
- 2,380 (8.4%) 2S-2 tractor-semitrailer trucks

1.2.2 GROSS VEHICLE WEIGHTS (Snyder et al 1985)

![Histogram of Gross Vehicle Weights]

- Scale: $G_{\text{VW max}} = 890$ kN; 40 bars 22.25 kN wide.
- Equivalent GVW:

$$G_{\text{VW e}} = \left( \frac{\sum n_i W_i^m}{\sum n_i} \right)^{1/m} = 239 \text{ kN}$$

where

$W_i =$ weight of $i$-th truck

$n_i =$ number of trucks of weight $W_i$

$m = 3 =$ rounded inverse slope of S-N curves
1.2 TRUCK LOADS ON HIGHWAYS

1.2.3 SPECIAL TRUCKS

**DOUBLE TRUCKS, DOUBLE TROUBLE?**

The truck industry is quietly urging the states to approve the use of longer trucks in the East and South. Automotive and highway safety groups will fight the effort.

**Automobile**
- Weighs up to 2,000-4,000 lbs.
- 60 ft.

**Tractor-semi-trailer**
- Weighs up to 93,000 lbs.
- 58 ft.

**Rocky Mountain double**
- Weighs up to 115,000 lbs.
- 110 ft.

**Triple**
- Weighs up to 135,000 lbs.
- 120 ft.

**Turnpike double**
- Weighs up to 150,000 lbs.

*Source: SHIMM plans for highway and area highways and AAA.*
1.3 FATIGUE DESIGN

1.3.1 LIMIT STATE

Steel bridges are designed for load-induced fatigue using one design truck with a constant spacing of 9.0 m between the 145-kN axles. A dynamic load allowance (IM) is added to the fatigue load. The truck is positioned transversely and longitudinally so as to produce the largest stress range at the detail.

The limit state equation is:

\[ y \Delta f \leq \Delta F_n \]

- The load factor \( y \) is obtained by normalizing the equivalent truck weight:

\[ \frac{\text{GVW}_e}{\text{GVW}_{\text{design}}} = \frac{239}{35 + 145 + 145} = 0.735 \]

This factor is rounded in the LRFD Bridge Specifications to:

\[ y = 0.75 \]

Although the LRFD Bridge Specifications call \( y \) a load factor, which suggests a margin of safety, it is fact an expression of Miner’s rule. The equivalent stress range and Miner’s rule are analogous concepts (Yamada 1975). It can be shown that the 27,513 trucks in the GVW histogram cause the same amount of fatigue damage as the same number of trucks of equivalent \( \text{GVW}_e = 239 \text{ kN} \). And this value is about equal to \( 0.75 \text{ GVW}_{\text{design}} \). The parameter \( y \) is then simply the root-mean-cube \( (m = 3) \) of all GVWs in the histogram normalized by the weight of the design truck.

- \( \Delta f \) is the calculated stress range at the detail due to the passage of the design truck.

- \( \Delta F_n \) is called the nominal fatigue resistance. It is actually calculated form the allowable S-N line, not the mean S-N line, and therefore should be called the design fatigue resistance. The resistance factor, which is already included in \( \Delta F_n \), can be calculated from the expression (Albrecht and Simon 1981):

\[ \varphi = 10^{-\frac{2s}{m}} \]

where for a given set of fatigue test data:

- \( s \) = standard deviation on logarithm of life
- \( m \) = inverse slope of S-N line

The resistance factor \( \varphi \) is the vertical distance between the mean and allowable S-N lines, at the same number of cycles.

The implicit resistance factor varies from \( \varphi = 0.73 \) for Category A rolled beams to \( \varphi = 0.86 \) for Category E welded cover plates (Albrecht and Rubeiz 1990).

The value of the intercept \( b \) in the table is for stress range in units of MPa. The other values, \( m \) and \( s \), have no units.
1.3.2 DESIGN LIFE

Bridges are designed for the following number of stress range cycles:

\[ N = 365 N_y \cdot ADTT \cdot p \cdot n \]

where

- \( N_y \) = 75 years, design life of short- and medium-span bridges
- \( ADTT \) = number of trucks per day in one direction averaged over the design life
- \( p \) = fraction of truck traffic in single lane; \( p = 1 \) for 1 lane, \( p = 0.85 \) for 2 lanes, and \( p = 0.80 \) for 3 or more lanes available to trucks.
- \( n \) = number of stress range cycles per truck passage (see tables below)

**Table 2 Number of Cycles per Truck Passage, n**

<table>
<thead>
<tr>
<th>Category and Type of Detail Tested</th>
<th>Longitudinal Members</th>
<th>Transverse Members</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept ( b )</td>
<td>Slope ( m )</td>
<td>Standard Deviation ( s )</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>----------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>A: rolled beam</td>
<td>13.785</td>
<td>3.178</td>
</tr>
<tr>
<td>B: welded beam</td>
<td>13.696</td>
<td>3.372</td>
</tr>
<tr>
<td>C: transverse stiffener</td>
<td>12.681</td>
<td>3.097</td>
</tr>
<tr>
<td>D: 100-mm attachment</td>
<td>12.177</td>
<td>3.071</td>
</tr>
<tr>
<td>E: welded cover plate</td>
<td>11.886</td>
<td>3.095</td>
</tr>
</tbody>
</table>

Example: Beltway around Washington, DC.

\[ N = 365 N_y \cdot ADTT \cdot p \cdot n = 365 \cdot 75 \cdot 9,000 \cdot 1.00 \cdot 1.0 \cdot 246 \cdot 10^6 \, \text{trucks} \]
1.3 FATIGUE DESIGN

1.3.3 FATIGUE RESISTANCE

LRFD Bridge Specifications

In terms of stress range:

\[
\begin{align*}
\text{For } \Delta F_n \leq 0.5 \Delta F_{TH} : & \quad \Delta F_n = \left( \frac{A}{N} \right)^{1/3} \quad \text{Fatigue II} \\
\text{For } \Delta F_n < 0.5 \Delta F_{TH} : & \quad \Delta F_n = 0.5 \Delta F_{TH}^{1.0} \quad \text{Fatigue I}
\end{align*}
\]

or in terms of fatigue life:

\[
\begin{align*}
\text{For } N \leq \frac{A}{(0.5 \Delta F_{TH})^3} : & \quad N = \frac{A}{\Delta F_n^3} \\
\text{For } N \geq \frac{A}{(0.5 \Delta F_{TH})^3} : & \quad N = \infty
\end{align*}
\]

Simplified Model

The following fatigue design equation accounts for the gradual transition between the finite and infinite regimes observed in tests. In addition only one single equation is needed (Albrecht et al 1994, Albrecht and Wright 1999).

In terms of stress range:

\[
\Delta F_n = \left( \frac{A}{N} + (0.5 \Delta F_{TH})^3 \right)^{1/3}
\]

or in terms of fatigue life:

\[
N = \frac{A}{\Delta F_n^3 - (0.5 \Delta F_{TH})^3}
\]

Figure 3 Design S-N Curves for Highway Bridges

<table>
<thead>
<tr>
<th>Table 3 Constant and Threshold for Design S-N Curves</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Detail Category</strong></td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>B'</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>C'</td>
</tr>
<tr>
<td>D</td>
</tr>
<tr>
<td>E</td>
</tr>
<tr>
<td>E'</td>
</tr>
</tbody>
</table>
1.3.4 BASIC DETAIL CATEGORIES

A — Plain Material
Base metal with rolled or cleaned surface.
Flame-cut edges with smoothness of 0.0025 mm or less.

B — Built-up Members
Base metal or weld metal in members without attachments, built-up shapes or plates connected by continuous fillet welds parallel to the direction of applied stress.

C and C' — Transverse Stiffeners
Base metal at toe of welds on girder webs or flanges adjacent to welded transverse stiffeners.

C — Short Attachments
Base metal of member subject to longitudinal loading and to which a plate is attached by fillet welds, $L < 50$ mm.

D — Short Attachments
Base metal of member subject to longitudinal loading and to which a plate is attached by fillet welds, $50$ mm $< L < 100$ mm or $12t$.

E and E' — Long Attachments
Base metal of member subject to longitudinal loading and to which a plate is attached by fillet welds, $L > 100$ mm or $12t$ and:

- when $t \leq 25$ mm ... E
- when $t > 25$ mm ... E'

For all other details see the LRFD Bridge Specifications.
1.3.5 DISTRIBUTION FACTORS FOR BEAM-SLAB BRIDGES

Bridges with Two or Three Girders — Interior Girder

Use lever rule:

Bridges with Two or Three Girders — Exterior Girder

Use lever rule:
\[ \Delta f = \frac{M_{\text{max}} - M_{\text{min}}}{S_x} \quad y \leq \Delta F \]

For \( \Delta F_n \geq 0.5 \Delta F_{TH} \):
\[ \Delta F_n = \left( \frac{A}{N} \right)^{1/3} \]

For \( \Delta F_n < 0.5 \Delta F_{TH} \):
\[ \Delta F_n = 0.5 \Delta F_{TH} \]
2.1 TRANSVERSE STIFFENERS ACTING AS CONNECTION PLATES

2.1.1 DESIGN RULES

- Transverse stiffeners shall be welded or bolted to both the compression and tension flanges when they act as connection plates for the following members:
  - Diaphragms
  - Cross frames
  - Floor beams

- In the absence of detailed analysis, the welded or bolted connections should be designed to resist a 90 kN lateral load for straight, non-skewed bridges. This value is a rule of thumb. Detailed analysis of force transfer is needed for curved or skewed bridges.

- Transverse stiffeners provided solely to prevent web buckling need not be welded to the tension flange.

2.1.2 CROSS FRAME CONNECTIONS


Figure 1 Cross Frame Attached to Transverse Stiffeners, I-girder Bridge

Figure 2 Cross Frame Attached to Transverse Stiffeners, Box-girder Bridge
1.3 Fatigue Design

Bridges with More Than Three Girders — Interior Girder

- Distribution factor for one design lane loaded:

\[ g = 0.06 + \left( \frac{S}{4300} \right)^{0.4} \left( \frac{S}{L} \right)^{0.3} \left( \frac{K_g}{L t_s^3} \right)^{0.1} \]

- Range of Validity:
  - \( 6,000 \text{ mm} \leq L < 73,000 \text{ mm} \)
  - \( 1,100 \text{ mm} \leq S < 4,900 \text{ mm} \)
  - \( 110 \text{ mm} \leq t_s < 300 \text{ mm} \)
  - \( N_b \geq 4 \)

where the longitudinal stiffness parameter is

\[ K_g = n(l + A e_g^2) \]

and

- \( A \) = area of stringer, beam or girder (mm²)
- \( l \) = moment of inertia of beam (mm⁴)
- \( K_g \) = longitudinal stiffness parameter
- \( L \) = span length of beam (mm)
- \( S \) = spacing of beams or webs (mm)
- \( e_g \) = distance between centers of gravity of basic beam and deck (mm)
- \( g \) = distribution factor
- \( n \) = modular ratio between beam and deck materials
- \( t_s \) = depth of concrete slab (mm)

Bridges with More Than Three Girders — Exterior Girder

- Use lever rule.
2.1.3 FLOOR BEAM CONNECTIONS

Figure 3 Floor Beams Attached to Transverse Bearing Stiffeners, I-girder Bridge

Figure 4 Floor Beam and Bracket Attached to Transverse Stiffeners, I-girder Bridge

2.1.4 STIFFENER-TO-FLANGE CONNECTIONS

Figure 5 Stiffener Welded to Tension Flange

Figure 6 Stiffener Bolted to Tension Flange
Figure 7 Stiffener Welded and Bolted to Tension Flange
2.2 LATERAL GUSSET PLATES

2.2.1 DESIGN RULES

Attachment to Flange
Lateral gusset plates should preferably be attached directly to a flange.

Attachment to Web
When it is not practical to attach them to a flange, lateral gusset plates may be attached to the web as follows to reduce distortion-induced stresses.

- **Stiffened Webs**
  - Lateral gusset plates should be located a vertical distance not less than one-half the flange width, \( t_f/2 \), above or below the flange.
  - Lateral gusset plates shall be centered on the stiffener, whether or not the plate is on the same side of the web as the stiffener.
  - When gusset plate and stiffener are on the same side of the web, they shall be attached to each other.
  - Transverse stiffeners acting as connection plates shall be continuous from the compression flange to the tension flange and shall be attached to both flanges.

- **Unstiffened Webs**
  - Lateral gusset plates should be located at least \( 150 \text{ mm} \) above or below the flange, but not less than one-half the flange width, \( t_f/2 \).

- **Lateral Bracing Members**
  - The ends of lateral bracing members on the lateral gusset plate shall be kept a minimum of \( 100 \text{ mm} \) from the web and any transverse stiffener.

---

**FIG. 1**— Lateral Gusset Plate Groove-welded to Flange Edge, I-girder Bridge

**FIG. 2**— Lateral Gusset Plate Fillet-welded to Top of Bottom Flange, I-girder Bridge
2.2.3 LATERAL GUSSET PLATE WELDED TO WEB

FIG. 3—Lateral Gusset Plate Welded to Web, Gusset Plate Not Slotted, I-girder Bridge

FIG. 4—Lateral Gusset Plate Welded to Web, Gusset Plate Slotted to Fit Around Stiffener, I-girder Bridge