Design for Fatigue of Structural Steel

By: Tim Kivisto, PE
AGENDA

- What is fatigue?
  - Examples of steel subjected to fatigue
- What triggers fatigue design?
  - Illustration of the “Stress Range” concept
  - Explanation of the “Threshold Stress” term
- Allowable stress range equation (A-3-1) from AISC
  - Overview of Fatigue Design Parameter tables
- Considerations for bolted / welded connections
- 6 Worked Questions
Safety Moment
Structural Steel Erection

- Use of proper fall protection equipment is mandated by OSHA
- Recent changes in OSHA regulations regarding fall protection
- When on site, if you see something, say something
What is fatigue?
What is fatigue?

- Applies to members and connections subject to high-cycle loading that induce sufficient stresses to initiate cracking and progressive failure from service live loads.

- Addressed in Appendix 3 of AISC 360-16 “Specification for Structural Steel Buildings” (and Commentary).
What is fatigue?

- What about dead load, wind loads, seismic loads?
  - Dead load is not cyclic ’always present
  - Wind load is cyclic but not usually strong enough to initiate cracking
  - Seismic design events are very infrequent

- Does this work for LRFD design or only ASD?
  - This is a *service load* stress check
    - Treat similar to deflection checks
Examples of Steel Subjected to Fatigue
Examples of Steel Subjected to Fatigue

- Manufacturing sector with highly cyclic live loading:
  - Bridge Cranes, Crane Runways, Monorails, Manufacturing Equip.
- Transportation sector:
  - Steel Bridges
Bridge Crane
Lifting Eye
Lifting Eye
Lifting Eye (Video)
Steel Bridges
What Triggers Design for Fatigue (per AISC)?
AISC Answer:

Steel members and connections subject to high-cycle loading within the elastic range of stresses of frequency and magnitude sufficient to initiate cracking and progressive failure
What triggers fatigue design?

But....

- If the number of lifetime live load cycles < 20,000  
  - fatigue consideration is *not* required
- If the live load stress range is less than the threshold stress, $F_{TH}$  
  - *no fatigue evaluation required*
- If the stress range is in full compression  
  - *no fatigue evaluation required*

Note that the provisions of Appendix 3 apply only to structures subject to temperatures less than 300°F.
Some Perspective on Load Cycles

What does 20,000 live load cycles look like?

- Design life of 25 years, crane is heavily loaded 1x per day x 5 days a week
  = 6,500 cycles (*fatigue check not required*)
- Design life of 25 years, crane is heavily loaded 3x per day x 5 days a week
  = 19,500 cycles (*fatigue check not technically required, < 20,000 cycles*)
- Design life of 50 years, crane is heavily loaded 15x per shift x 2 shifts x 5 days a week
  = 390,000 cycles (*fatigue check required!!*)
Stress Range

- For elements in complete compression or tension under cyclic loading or shear applied in single direction:

  » Stress Range = (T_{max} or C_{max} or V_{max}) – 0

- For elements that see both tension & compression or shear in opposing directions, the stress range is the absolute value of the difference of the extreme values (using negative for one and positive for the other):

  » Stress Range = |T_{max} – C_{max}| or |V_{max, +ve} – V_{max, -ve}|
Visualization of Stress Range
The Threshold Stress ($F_{TH}$) or threshold allowable stress range is the stress level below which fatigue design does not need to be considered.

From Table A-3.1 (shown later), threshold stress varies for each type of component/connection and varies from 24 ksi → 2.6 ksi
Put it another way:

“Threshold allowable stress range is the maximum stress range for indefinite design life.”
Threshold Stress vs Stress Range
Allowable stress range equation
Allowable Stress Range

In plain material and welded joints, the range of stress due to the applied cyclic loads shall not exceed the allowable stress range computed as follows.

(a) For stress categories A, B, B’, C, D, E and E’, the allowable stress range, \( F_{SR} \), shall be determined by Equation A-3-1 or A-3-1M, as follows:

\[
F_{SR} = 1,000 \left( \frac{C_f}{n_{SR}} \right)^{0.333} \geq F_{TH} \quad \text{(A-3-1)}
\]

\[
F_{SR} = 6900 \left( \frac{C_f}{n_{SR}} \right)^{0.333} \geq F_{TH} \quad \text{(A-3-1M)}
\]

where

\( C_f \) = constant from Table A-3.1 for the fatigue category
\( F_{SR} \) = allowable stress range, ksi (MPa)
\( F_{TH} \) = threshold allowable stress range, maximum stress range for indefinite design life from Table A-3.1, ksi (MPa)
\( n_{SR} \) = number of stress range fluctuations in design life

*Updated in AISC 360-16
(b) For stress category F, the allowable stress range, $F_{SR}$, shall be determined by Equation A-3-2 or A-3-2M as follows:

$$F_{SR} = 100 \left( \frac{1.5}{n_{SR}} \right)^{0.167} \geq 8 \text{ ksi}$$  \hspace{1cm} (A-3-2)

$$F_{SR} = 690 \left( \frac{1.5}{n_{SR}} \right)^{0.167} \geq 55 \text{ MPa}$$  \hspace{1cm} (A-3-2M)

*Updated in AISC 360-16*
(c) For tension-loaded plate elements connected at their end by cruciform, T or corner details with partial-joint-penetration (PJP) groove welds transverse to the direction of stress, with or without reinforcing or contouring fillet welds, or if joined with only fillet welds, the allowable stress range on the cross section of the tension-loaded plate element shall be determined as the lesser of the following:
Fatigue Design Parameter Tables

- See Table A-3.1 starting on page 16.1-196 *

(8 sections over 10 pages + accompanying diagrams)

- Section 1 – Plain material away from any welding
- Section 2 – Connected material in mechanically fastened joints
- Section 3 – Welded joints joining components of built-up members
- Section 4 – Longitudinal filled welded end connections
- Section 5 – Welded joints transverse to direction of stress
- Section 6 – Base metal at welded transverse member connections
- Section 7 – Base metal at short attachments
- Section 8 - Miscellaneous
### TABLE A-3.1

**Fatigue Design Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Stress Category</th>
<th>Constant ( C_r )</th>
<th>( \text{Threshold Fracture Stress} ) (MPa)</th>
<th>Potential Crack Initiation Point</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SECTION 1—PLAIN MATERIAL AWAY FROM ANY WELDING</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1 Base metal, except noncoated weathering steel, with as-rolled or cleaned surfaces; flame-cut edges with surface roughness value of 1,000 µm (25 µm) or less, but without reentrant corners.</td>
<td>A</td>
<td>25</td>
<td>24 (165)</td>
<td>Away from all welds or structural connections</td>
</tr>
<tr>
<td>1.2 Noncoated weathering steel base metal with as-rolled or cleaned surfaces; flame-cut edges with surface roughness values of 1,000 µm (25 µm) or less, but without reentrant corners.</td>
<td>B</td>
<td>12</td>
<td>16 (110)</td>
<td>Away from all welds or structural connections</td>
</tr>
<tr>
<td>1.3 Members with reentrant corners at corners, cuts, blockouts or other geometrical discontinuities, except weld access holes.</td>
<td>C</td>
<td>4.4</td>
<td>10 (65)</td>
<td>At any external edge or at hole perimeter</td>
</tr>
<tr>
<td>( R \geq 1 \text{ in.} (25 \text{ mm}) ), with radius, ( R ), formed by prefilleting, subpunching, and reaming or thermally cut and ground to a bright metal surface.</td>
<td>C</td>
<td>4.4</td>
<td>10 (65)</td>
<td>At reentrant corner of weld access hole</td>
</tr>
<tr>
<td>( R \leq 1/8 \text{ in.} (10 \text{ mm}) ) and the radius, ( R ), need not be ground to a bright metal surface.</td>
<td>E'</td>
<td>0.39</td>
<td>2.6 (18)</td>
<td></td>
</tr>
<tr>
<td>1.4 Rolled cross sections with weld access holes made to requirements of Section 21.6.</td>
<td>C</td>
<td>4.4</td>
<td>10 (65)</td>
<td></td>
</tr>
<tr>
<td>Access hole ( R \geq 1 \text{ in.} (25 \text{ mm}) ) with radius, ( R ), formed by prefilleting, subpunching, and reaming or thermally cut and ground to a bright metal surface.</td>
<td>C</td>
<td>4.4</td>
<td>10 (65)</td>
<td></td>
</tr>
<tr>
<td>Access hole ( R \leq 1/8 \text{ in.} (10 \text{ mm}) ) and the radius, ( R ), need not be ground to a bright metal surface.</td>
<td>E'</td>
<td>0.39</td>
<td>2.6 (18)</td>
<td></td>
</tr>
<tr>
<td>1.5 Members with drilled or reamed holes.</td>
<td>D</td>
<td>2.2</td>
<td>7 (48)</td>
<td>In net section originating at side of the hole</td>
</tr>
<tr>
<td>Holes containing pretensioned bolts.</td>
<td>G</td>
<td>4.4</td>
<td>10 (65)</td>
<td></td>
</tr>
<tr>
<td>Open holes without bolts.</td>
<td>G</td>
<td>4.4</td>
<td>10 (65)</td>
<td>In net section originating at side of the hole</td>
</tr>
</tbody>
</table>

**Illustrative Typical Examples**

<table>
<thead>
<tr>
<th>SECTION 1—PLAIN MATERIAL AWAY FROM ANY WELDING</th>
<th>1.1 and 1.2</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Illustrative Typical Examples" /></td>
<td><img src="image2.png" alt="Illustrative Typical Examples" /></td>
</tr>
</tbody>
</table>

| ![Illustrative Typical Examples](image3.png) | 1.3 |
| ![Illustrative Typical Examples](image4.png) | ![Illustrative Typical Examples](image5.png) |

| ![Illustrative Typical Examples](image6.png) | 1.4 |
| ![Illustrative Typical Examples](image7.png) | ![Illustrative Typical Examples](image8.png) |

| ![Illustrative Typical Examples](image9.png) | 1.5 |
| ![Illustrative Typical Examples](image10.png) | ![Illustrative Typical Examples](image11.png) |
### TABLE A-3.1 (continued)
**Fatigue Design Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Stress Category</th>
<th>Constant $C_I$</th>
<th>Threshold $F_{th}$ (ksi)</th>
<th>Potential Crack Initiation Point</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SECTION 2—CONNECTED MATERIAL IN MECHANICALLY FASTENED JOINTS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1 Gross area of base metal in lap joints connected by high-strength bolts</td>
<td>B</td>
<td>12</td>
<td>16 (110)</td>
<td>Through gross section near hole</td>
</tr>
<tr>
<td>in joints satisfying all requirements for slip-critical connections</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2 Base metal at net section of high-strength bolted joints, designed on</td>
<td>B</td>
<td>12</td>
<td>16 (110)</td>
<td>In net section originating at</td>
</tr>
<tr>
<td>the basis of bearing resistance, but fabricated and installed to all</td>
<td></td>
<td></td>
<td></td>
<td>side of hole</td>
</tr>
<tr>
<td>requirements for slip-critical connections</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3 Base metal at the net section of</td>
<td>C</td>
<td>4.4</td>
<td>10 (69)</td>
<td>In net section originating at</td>
</tr>
<tr>
<td>riveted joints</td>
<td></td>
<td></td>
<td></td>
<td>side of hole</td>
</tr>
<tr>
<td>2.4 Base metal at net section of eyebolt head or pin plate</td>
<td>E</td>
<td>1.1</td>
<td>4.5 (51)</td>
<td>In net section originating at</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>side of hole</td>
</tr>
</tbody>
</table>

### Illustrative Typical Examples

**SECTION 2—CONNECTED MATERIAL IN MECHANICALLY FASTENED JOINTS**

2.1 As seen with lap plate removed
   (Note: Figures are for slip-critical bolted connections.)

2.2 As seen with lap plate removed
   (Note: Figures are for bolted connections designed to bear, meeting the requirements of slip-critical connections.)

2.3 As seen with lap plate removed
   (Note: Figures are for snugly tightened bolts, rivets, or other mechanical fasteners.)

2.4
### TABLE A-3.1 (continued)
**Fatigue Design Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Stress Category</th>
<th>Constant $C_I$</th>
<th>Threshold $F_{100}$ (MPa)</th>
<th>Potential Crack Initiation Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5 Base metal and weld metal in or adjacent to transverse TJP groove welds or butt welds with an opening left in place</td>
<td>D</td>
<td>2.2</td>
<td>7 (48)</td>
<td>From the toe of the groove weld or the toe of the root extending into base metal</td>
</tr>
<tr>
<td>Tack welds inside groove</td>
<td>E</td>
<td>1.1</td>
<td>4.5 (31)</td>
<td>Tack welds outside the groove and not closer than 3/8 in. (19 mm) to the edge of base metal</td>
</tr>
<tr>
<td>5.6 Base metal and weld metal at transverse welds connecting tension-loaded plate elements using TJP groove welds in butt, T- or corner joints, with random or containing flutes; $F_{100}$ shall be the smaller of the toe crack or root crack allowable stress range. Crack initiating from weld toe. Crack initiating from weld root</td>
<td>C</td>
<td>4.4</td>
<td>10 (69)</td>
<td>Initiation from weld toe extending into base metal</td>
</tr>
<tr>
<td>C' See Eq. A-3.3 or A-3.5</td>
<td></td>
<td></td>
<td></td>
<td>Initiation at weld root extending into and through weld</td>
</tr>
<tr>
<td>5.7 Base metal and weld metal at transverse welds connecting tension-loaded plate elements using a pair of flange welds on opposite sides of the plate; $F_{100}$ shall be the smaller of the toe crack or root crack allowable stress range. Crack initiating from weld toe. Crack initiating from weld root</td>
<td>C</td>
<td>4.4</td>
<td>10 (69)</td>
<td>Initiation from weld toe extending into base metal</td>
</tr>
<tr>
<td>C' See Eq. A-3.3 or A-3.5</td>
<td></td>
<td></td>
<td></td>
<td>Initiation at weld root extending into and through weld</td>
</tr>
<tr>
<td>5.8 Base metal of tension-loaded plate elements and on butt joints and fillet welds on or near the toe of transverse welds adjacent to welded transverse stiffeners</td>
<td>C</td>
<td>4.4</td>
<td>10 (69)</td>
<td>From geometrical discontinuity at toe of fillet extending into base metal</td>
</tr>
</tbody>
</table>

### Illustrative Typical Examples

#### SECTION 5—WELDED JOINTS TRANSVERSE TO DIRECTION OF STRESS

5.5 Category D

5.5 Category E

5.6 Tooth Crack Category C

5.7 Tooth Crack Category C

5.8 Tooth Crack Category C

5.9 Tooth Crack Category C

5.10 Tooth Crack Category C

5.11 Tooth Crack Category C

5.12 Tooth Crack Category C
<table>
<thead>
<tr>
<th>Description</th>
<th>Stress Category</th>
<th>Constant $C_T$</th>
<th>Threshold $F_{th}$ (MPa)</th>
<th>Potential Crack Initiation Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1 Base metal at steel headed stud anchors attached by fillet weld or automatic stud welding</td>
<td>C</td>
<td>4.4</td>
<td>10 (39)</td>
<td>At toe of weld in base metal</td>
</tr>
<tr>
<td>8.2 Shear on throat of any fillet weld, continuous or intermittent, longitudinal or transverse</td>
<td>F</td>
<td>See Eq. A-3-2 or A-3-2M</td>
<td>See Eq. A-3-2 or A-3-2M</td>
<td>Initiating at the root of the fillet weld, extending into the weld</td>
</tr>
<tr>
<td>8.3 Base metal at plug or slot welds</td>
<td>E</td>
<td>1.1</td>
<td>4.5 (31)</td>
<td>Initiating in the base metal at the end of the plug or slot weld, extending into the base metal</td>
</tr>
<tr>
<td>8.4 Shear on plug or slot welds</td>
<td>F</td>
<td>See Eq. A-3-2 or A-3-2M</td>
<td>See Eq. A-3-2 or A-3-2M</td>
<td>Initiating in the weld at the faying surface, extending into the weld</td>
</tr>
<tr>
<td>8.5 High-strength bolts, common bolts, threaded anchor rods, and hanger rods, whether pretensioned in accordance with Table J3.1 or J3.1M, or snug-tightened with cut, ground or rolled threads; stress range on tensile stress area due to applied cyclic load plus prying action, when applicable</td>
<td>G</td>
<td>0.39</td>
<td>7 (18)</td>
<td>Initiating at the root of the threads, extending into the tighten</td>
</tr>
</tbody>
</table>

Illustrative Typical Examples

SECTION 8—MISCELLANEOUS

8.1
(a) ![Diagram](image1)
(b) ![Diagram](image2)

8.2
(a) ![Diagram](image3)
(b) ![Diagram](image4)
(c) ![Diagram](image5)

8.3
(a) ![Diagram](image6)
(b) ![Diagram](image7)

8.4
(a) ![Diagram](image8)
(b) ![Diagram](image9)

8.5
(a) ![Diagram](image10)
(b) ![Diagram](image11)
(c) ![Diagram](image12)
(d) ![Diagram](image13)
Bolts and Threaded Parts
Bolts and Threaded Parts

- Section 3.4:
  - For mechanically fastened connections loaded in shear, use Section 2 of Table A-3.1
  - For bolts (or anchor rods), the maximum range of tensile stress from axial load + moment + prying action shall follow equation A-3-1 and use $C_f$ and $F_{TH}$ from Stress Category G, Case 8.5
    - Use net tensile area from applied axial load, moment, and prying action
# Bolts and Threaded Parts

| 8.5 High-strength bolts, common bolts, threaded anchor rods, and hanger rods, whether pretensioned in accordance with Table J3.1 or J3.1M, or snug-tightened with cut, ground or rolled threads; stress range on tensile stress area due to applied cyclic load plus prying action, when applicable | G | 0.39 | 7 (48) | Initiating at the root of the threads, extending into the fastener |

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![Diagram](image-url)
Welded Components
Welded Components

- Welds frequently feature in fatigue design

- 4 out of 8 sections of Table A-3.1 have “weld” in the title and the misc. section has 4 weld sub-sections
Fatigue Design Parameter Tables (Review)

- See Table A-3.1 starting on page 16.1-196 *

(8 sections over 10 pages + accompanying diagrams)

- Section 1 – Plain material **away from any welding**
- Section 2 – Connected material in mechanically fastened joints
- Section 3 – **Welded** joints joining components of built-up members
- Section 4 – Longitudinal filled **welded** end connections
- Section 5 – **Welded** joints transverse to direction of stress
- Section 6 – Base metal at **welded** transverse member connections
- Section 7 – Base metal at short (**welded**) attachments
- Section 8 – Miscellaneous (4 out of 5 sub-categories are **welded** connections)
Good design practice for weld design is to remain below the threshold stress in the weld and in the connected parts near the weld.

“EOR shall provide complete details including weld sizes or shall specify the planned cycle life and max. range of moments, shears and reactions for the connections.”

3.1. GENERAL PROVISIONS

The fatigue resistance of members consisting of shapes or plate shall be determined when the number of cycles of application of live load exceeds 20,000. No evaluation of fatigue resistance of members consisting of HSS in building-type structures subject to code mandated wind loads is required. When the applied cyclic stress range is less than the threshold allowable stress range, \( F_{c1y} \), no further evaluation of fatigue resistance is required. See Table A-3.1.

The engineer of record shall provide either complete details including weld sizes or shall specify the planned cycle life and the maximum range of moments, shears and reactions for the connections.

The provisions of this Appendix shall apply to stresses calculated on the basis of the applied cyclic load spectrum. The maximum permitted stress due to peak cyclic loads shall be 0.665\( F_{c1y} \). In the case of a stress reversal, the stress range shall be computed as the numerical sum of maximum repeated tensile and compressive stresses or the numerical sum of maximum shearing stresses of opposite direction at the point of probable crack initiation.

The cyclic load resistance determined by the provisions of this Appendix is applicable to structures with suitable corrosion protection or subject only to mildly corrosive atmospheres, such as normal atmospheric conditions.

The cyclic load resistance determined by the provisions of this Appendix is applicable only to structures subject to temperatures not exceeding 300°F (150°C).
Worked Questions (6)
Question 1:
A component will be cyclically loaded 5 times per day, every day, for 10 years. Design for fatigue is required, true or false? (Why / Why not?)

$$n_{SR} = 5 \times 365 \times 10 = 18,250$$

TRUE

FALSE

Fatigue consideration not required
What triggers fatigue design? (Review)

- But....
  - If the number of lifetime live load cycles < 20,000, fatigue consideration is _not_ required
  - If the live load stress range is less than the threshold stress, $F_{TH}$, _no fatigue evaluation is needed_
  - Stress ranges that are full in compression require _no fatigue evaluation_

- Note that the provisions of Appendix 3 apply only to structures subject to temperatures less than 300°F.
Question 2:
A compression-only column will be cyclically loaded 5 times per day for 25 years. Design for fatigue is required, true or false?
Why / Why not?

\[ n_{SR} = 5 \times 365 \times 25 = 45,625 \]

**TRUE**

**FALSE**

Fatigue consideration not required
What triggers fatigue design? (Review)

- But....
  - If the number of lifetime live load cycles < 20,000, fatigue consideration is *not* required
  - If the live load stress range is less than the threshold stress, $F_{TH}$, *no fatigue evaluation is needed*
  - Stress ranges that are full in compression require *no fatigue evaluation*

- Note that the provisions of Appendix 3 apply only to structures subject to temperatures less than 300°F.
Question 3:
The threshold stress for a steel component is 16 ksi with 50,000 cycles of loading over its lifetime. The stress of the component fluctuates between 5 ksi in compression and 14 ksi in tension. Design for fatigue is required, true or false? Why / why not?

1: $n_{SR} = 50,000$

2: Actual stress range = difference between 14 ksi (tension) and 5 ksi (compression).

<table>
<thead>
<tr>
<th>TRUE</th>
<th>FALSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>True, number of cycles &gt; 20,000 and stress range (19 ksi) &gt; threshold stress range (= 16 ksi)</td>
<td></td>
</tr>
</tbody>
</table>
Question 4:

For the previous question, what is the allowable design stress range according to equation A-3-1 assuming the component is plain material in Stress Category B?
Question 4:

For the previous question, what is the allowable design stress range according to equation A-3-1 assuming the component is plain material in Stress Category B?

Recall that $F_{SR} = 1000 \times \left(\frac{C_f}{n_{SR}}\right)^{0.333}$

1: Look up Constant, $C_f$
### TABLE A-3.1
Fatigue Design Parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Stress Category</th>
<th>Constant C&lt;sub&gt;i&lt;/sub&gt;</th>
<th>F&lt;sub&gt;th&lt;/sub&gt; (MPa)</th>
<th>Potential Crack Initiation Point</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SECTION 1—PLAIN MATERIAL AWAY FROM ANY WELDING</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1 Basic metal, except noncoated weathering steel, with as-rolled or</td>
<td>A</td>
<td>25</td>
<td>24 (166)</td>
<td>Away from all heads or structural connections</td>
</tr>
<tr>
<td>cleaned surfaces; flame-cut edges with surface roughness value of 1,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>μm (25 μm) or less, but without reentrant corners</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2 Noncoated weathering steel basic metal with as-rolled or cleaned</td>
<td>R</td>
<td>12</td>
<td>16 (110)</td>
<td>Away from all heads or structural connections</td>
</tr>
<tr>
<td>surfaces; flame-cut edges with surface roughness value of 1,000 μm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(25 μm) or less, but without reentrant corners</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3 Members with reentrant corners at edges, cuts, blockouts or other</td>
<td>C</td>
<td>4.4</td>
<td>10 (60)</td>
<td>At any external edge or at hole perimeter</td>
</tr>
<tr>
<td>geometrical discontinuities, except weld access holes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R ≥ 1 in. (25 mm), with radius, R, formed by prefilling,</td>
<td>E'</td>
<td>0.39</td>
<td>2.6 (18)</td>
<td></td>
</tr>
<tr>
<td>subpunching and reaming or thermally cut and ground to a bright</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>metal surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R ≥ 3/8 in. (10 mm) and the radius, R, need not be ground to a bright</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>metal surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4 Rolled cross sections with weld access holes made to requirements</td>
<td>C</td>
<td>4.4</td>
<td>10 (60)</td>
<td>At reentrant corner of weld access hole</td>
</tr>
<tr>
<td>of Section 21.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Access hole R ≥ 1 in. (25 mm) with radius, R, formed by prefilling,</td>
<td>E'</td>
<td>0.39</td>
<td>2.6 (18)</td>
<td></td>
</tr>
<tr>
<td>subpunching and reaming or thermally cut and ground to a bright</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>metal surface</td>
<td></td>
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<tr>
<td>Access hole R ≥ 3/8 in. (10 mm) and the radius, R, need not be</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ground to a bright metal surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5 Members with drilled or reamed holes</td>
<td>C</td>
<td>4.4</td>
<td>10 (60)</td>
<td>In net section originating at side of the hole</td>
</tr>
<tr>
<td>Holes containing pretensioned bolts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open holes without bolts</td>
<td>D</td>
<td>2.2</td>
<td>7 (48)</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE A-3.1 (continued)
Fatigue Design Parameters

<table>
<thead>
<tr>
<th>Illustrative Typical Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SECTION 1—PLAIN MATERIAL AWAY FROM ANY WELDING</strong></td>
</tr>
<tr>
<td>1.1 and 1.2</td>
</tr>
<tr>
<td>(a)</td>
</tr>
<tr>
<td>(b)</td>
</tr>
<tr>
<td>(c)</td>
</tr>
<tr>
<td>1.3</td>
</tr>
<tr>
<td>(a)</td>
</tr>
<tr>
<td>(b)</td>
</tr>
<tr>
<td>(c)</td>
</tr>
<tr>
<td>1.4</td>
</tr>
<tr>
<td>(a)</td>
</tr>
<tr>
<td>1.5</td>
</tr>
<tr>
<td>(a)</td>
</tr>
<tr>
<td>(b)</td>
</tr>
</tbody>
</table>
Question 4:

For the previous question, what is the allowable design stress range according to equation A-3-1 assuming the component is plain material in Stress Category B?

Recall that $F_{SR} = 1000 \times \left(\frac{C_f}{n_{SR}}\right)^{0.333}$

1: Look up Constant, $C_f = 12$
Question 4:

For the previous question, what is the allowable design stress range according to equation A-3-1 assuming the component is plain material in Stress Category B?

Recall that $F_{SR} = 1000 \times \left(\frac{C_f}{n_{SR}}\right)^{0.333}$
1: Look up Constant, $C_f = 12$
2: Recall that $N = 50,000$ (from previous question)
$F_{SR} = \left(\frac{C_f}{N}\right)^{0.333} = 62$ ksi (!!)...note the small “N”
Question 4:

For the previous question, what is the allowable design stress range according to equation A-3-1 assuming the component is plain material in Stress Category B?

Recall that $F_{SR} = 1000 \times \left( \frac{C_f}{n_{SR}} \right)^{0.333}$

1: Look up Constant, $C_f = 12$

2: Recall that $n_{SR} = 50,000$ (from previous question)

$\Rightarrow F_{SR} = 1000 \times \left( \frac{C_f}{n_{SR}} \right)^{0.333} = 62 \text{ ksi} \quad (!!)...\text{note the small } n_{SR} \text{“} \%

*Note that the maximum permitted stress due to peak cyclic loads is $0.66 F_y$
Question 5:

What is the design stress range for a \( \frac{3}{4} \)" dia. A325 bolt that is loaded 300,000 times cyclically? The bolt takes up to 5 kips in tension (3 kips from direct tension and 2 kips from moment)

Is the bolt OK?
8.5 High-strength bolts, common bolts, threaded anchor rods, and hanger rods, whether pretensioned in accordance with Table J3.1 or J3.1M, or snug-tightened with cut, ground or rolled threads; stress range on tensile stress area due to applied cyclic load plus prying action, when applicable

<table>
<thead>
<tr>
<th>$C_f$</th>
<th>$F_{TH}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.39</td>
<td>7 (48)</td>
</tr>
</tbody>
</table>

Initiating at the root of the threads, extending into the fastener

8.5

(a) Crack sites

(b) Crack sites

(c) Crack sites

(d)
Question 5:

What is the design stress range for a ¾” dia. A325 bolt that is loaded 300,000 times cyclically? The bolt takes up to 5 kips in tension (3 kips from direct tension and 2 kips from moment)

Is the bolt OK?

Recall that \( F_{SR} = 1000 \times \left( \frac{C_f}{n_{SR}} \right)^{0.333} \)

1: Look up Constant, \( C_f = 0.39, \) \( F_{TH} = 7 \) ksi, \( n_{SR} = 300,000 \)
Question 5:

What is the design stress range for a ¾” dia. A325 bolt that is loaded 300,000 times cyclically? The bolt takes up to 5 kips in tension (3 kips from direct tension and 2 kips from moment)

Is the bolt OK?

Recall that $F_{SR} = 1000 \times (C_f / n_{SR})^{0.333}$

1: Look up Constant, $C_f = 0.39$, $F_{TH} = 7 \text{ ksi}$, $n_{SR} = 300,000$

2: $F_{SR} = 1000 \times (C_f / n_{SR})^{0.333} = 10.9 \text{ ksi}$
Question 5:

What is the design stress range for a ¾” dia. A325 bolt that is loaded 300,000 times cyclically? The bolt takes up to 5 kips in tension (3 kips from direct tension and 2 kips from moment)

Is the bolt OK?

Recall that $F_{SR} = 1000 \times \left(\frac{C_f}{n_{SR}}\right)^{0.333}$

1: Look up Constant, $C_f = 0.39$, $F_{TH} = 7$ ksi, $n_{SR} = 300,000$

2: $F_{SR} = 1000 \times \left(\frac{C_f}{N}\right)^{0.333} = 10.9$ ksi

3: Actual bolt stress range = 5 kips / $A_{bolt} = 11.3$ ksi
Question 5:

What is the design stress range for a ¾” dia. A325 bolt that is loaded 300,000 times cyclically? The bolt takes up to 5 kips in tension (3 kips from direct tension and 2 kips from moment).

Is the bolt OK?

Recall that $F_{SR} = 1000 \times (C_f / n_{SR})^{0.333}$

1: Look up Constant, $C_f = 0.39$, $F_{TH} = 7$ ksi, $n_{SR} = 300,000$

2: $F_{SR} = 1000 \times (C_f / N)^{0.333} = 10.9$ ksi

3: Actual bolt stress range = 5 kips / $A_{bolt} = 11.3$ ksi

→ Since actual stress = 11.3 ksi > $F_{SR}$ BOLT NOT OK!
Question 6:

A diagonal brace on a piece of equipment experiences 1 ksi in compression and 2 ksi in tension. It is loaded approximately 5 times per minute, 24 hours per day, 7 days per week. The desired minimum design life is 10 years ($n_{SR} = 26,280,000$).

The brace (2L 6x4x7/8”) is longitudinally welded in an end connection to a gusset plate. What is the allowable stress range? Is the member sufficient at this connection?
Question 6:

1: Stress range = 3ksi, \( n_{SR} = 26,280,000 \), longitudinally welded brace 2L 6x4x7/8”:

**SECTION 4—LONGITUDINAL FILLET WELDED END CONNECTIONS**

4.1 Base metal at junction of axially loaded members with longitudinally welded end connections; welds are on each side of the axis of the member to balance weld stresses

\[ t_{w} \leq 0.5 \text{ in. (13 mm)} \]

\[ t_{w} > 0.5 \text{ in. (13 mm)} \]

where

\[ t = \text{connected member thickness, as shown in Case 4.1 figure, in. (mm)} \]

<table>
<thead>
<tr>
<th>( E )</th>
<th>( E' )</th>
<th>( 4.5 ) (31)</th>
<th>( 2.6 ) (19)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>0.39</td>
<td>Initiating from end of any weld termination extending into the base metal</td>
<td></td>
</tr>
</tbody>
</table>

(a) (b)
Question 6:

1: Stress range = 3ksi, \(n_{SR} = 26,280,000\), longitudinally welded brace 2L 6x4x7/8”.

2: \(F_{SR} = 1000 \times (C_f / n_{SR})^{0.333}\) where \(C_f = 1.1\) or 0.39 depending on “t”

(...what was member thickness??)

since \(t > 0.5\) in, \(C_f = 0.39\) and \(F_{TH} = 2.6\) ksi

\(\rightarrow F_{SR} = 2.47\) ksi but since less than \(F_{TH}\), \(F_{SR} = 2.6\) ksi
Question 6:

1: Stress range = 3ksi, $n_{SR} = 26,280,000$, longitudinally welded brace 2L 6x4x7/8”.

2: $F_{SR} = 1000 \times (C_f / n_{SR})^{0.333}$ where $C_f = 1.1$ or 0.39 depending on “t”
   
   (...what was member thickness??)
   
   since $t > 0.5$ in, $C_f = 0.39$ and $F_{TH} = 2.6$ ksi
   
   $\rightarrow F_{SR} = 2.47$ ksi but since less than $F_{TH}$, $F_{SR} = 2.6$ ksi

Is the brace adequately sized?

   $\rightarrow$ NO! Since actual stress range = 3 ksi > $F_{SR} = 2.6$ ksi
APPENDIX 3

FATIGUE

When the load rate of fatigue is a design consideration, its severity is most significantly affected by the number of load applications, the magnitude of the stress range, and the severity of the stress concentration associated with particular details. Forces of fatigue are not nor-

mally encountered in building design; however, when encountered, it is the severity to great enough fatigue to concern and all provisions of this Appendix must be satisfied.

3.1. GENERAL PROVISIONS

This Appendix deals with high cycle fatigue (i.e., > 10^6 cycles); this behavior occurs when elastic strains are involved. In situations where plastic (plastic) strains are involved, fatigue cracks may initiate at stress levels > 20% yield—

perhaps as few as a meter. However, under the conditions presented in this Appen-
dix, low cycle fatigue appears to be prevalent in metallic structures. It is because the appli-
cable cyclic stresses may range from 150 to 700 ksi. At low levels of cyclic stress, a crack can initiate when the stress range is less than the fatigue strength of the material, regardless of the number of cycles of load.

This load of stress is defined as the fatigue strength, S_{f}.

Examine test programs using full-scale specimens, subjected to laboratory stress

analyses, have confirmed the following general conclusions (Shoemaker et al., 1970; Fath et al., 1974):

(1) Stress range and stress severity are the dominant stress variables for welded details and beams.

(2) Other variables such as minimum stress, mean stress and maximum stress are not significant for design purposes.

(3) Structural details with a specified minimum yield stress of 56 to 100 ksi (320 to

689 MPa) do not exhibit significantly different fatigue strengths for given welded details fabricated in the same manner.

Fatigue crack growth rates are generally inversely proportional to the modulus of elasticity and surface crack length. Temperature, crack length, and stress are essential in the same way for fracture temperatures (Huntington et al., 1972). The Appendix is conserva-
tively limited to applications involving temperatures not exceeding 200°F (93°C). Elevated temperature applications may also have extensions of the fatigue crack growth rates that are not con-

sidered by the Appendix. The Appendix does not have a lower temperature limit because fatigue crack growth rates are lower. Fatigue tests at a low as -30°F (-34°C) have been conducted with no observables changes in crack growth rates (Roberts et al., 1963). It should be recognized
REVIEW
What is fatigue and where does it typically occur?

What triggers fatigue design?
  - Illustration of the “Stress Range” concept
  - Explanation of the “Threshold Stress” term

Allowable stress range equation (A-3-1) from AISC
  - Overview of Fatigue Design Parameter tables

Considerations for bolted / welded connections

Example questions
QUESTIONS AND DISCUSSION