

Night School 23: Topics on Industrial Building Design and Design of Non-building Structures

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**AISC**
Night School



Session 5 – Fatigue
July 21, 2020



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Course Description

Fatigue Design for Industrial Structures July 21, 2020

This session will provide an introduction to fatigue based on AISC 360, Appendix 3. The issues of inadvertent restraint will be reviewed and details to avoid these issues will be presented. The session will present application of the fatigue provisions in a design example.



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Learning Objectives

- Review of fatigue design fundamentals
- Review of AISC 360 Appendix 3
- Describe the role of good detailing in designing for fatigue
- Illustrate application of AISC Appendix 3 through various examples



Night School 23: Industrial Structures

Session 5: Fatigue Design for Industrial Structures

July 21, 2020



Jules Van de Pas, PE, SE
CSD Structural Engineers



INTRODUCTION

SESSION 1 INTRODUCTION AND CODE PROVISIONS

SESSION 2 INDUSTRIAL BUILDINGS – PART 1

SESSION 3 INDUSTRIAL BUILDINGS – PART 2

SESSION 4 CRANE SUPPORTING STRUCTURES

SESSION 5 FATIGUE DESIGN FOR INDUSTRIAL STRUCTURES

SESSION 6 HIGH & LOW TEMPERATURE DESIGN FOR INDUSTRIAL STRUCTURES

SESSION 7 NON-BUILDING STRUCTURES –PART 1

SESSION 8 NON-BUILDING STRUCTURES –PART 2



SESSION 5: FATIGUE DESIGN FOR INDUSTRIAL STRUCTURES

LEARNING OBJECTIVES:

1. Review of fatigue design fundamentals
2. Review of AISC 360 Appendix 3 (Included in the Handouts)
3. Illustrate application of AISC Appendix 3 through various examples



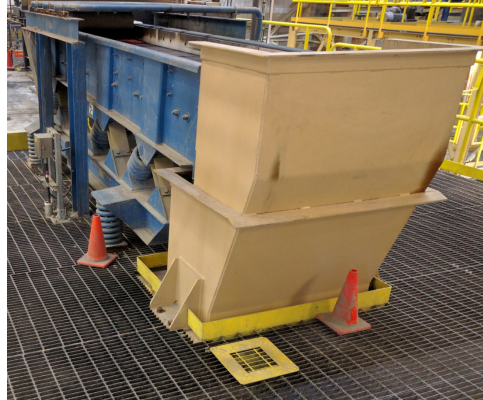
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BRIDGE CRANE SUPPORTS



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SUPPORTS FOR RECIPROCATING EQUIPMENT



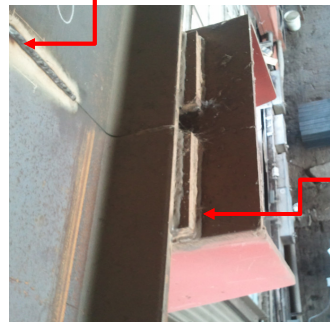
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FATIGUE DESIGN AND GOOD DETAILING PRACTICE ARE BOTH REQUIRED TO ENSURE GOOD RESULTS

Welded tie-back



Crane girder webs welded together



Crane girder welded to seat



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FATIGUE DEFINITIONS:

Fatigue is the process of cumulative damage in a benign environment that is caused by repeated fluctuating loads.

The same phenomena in the presence of an aggressive environment is corrosion fatigue.

FRACTURE & FATIGUE CONTROL IN STRUCTURES Applications of Fracture Mechanics John Barsom & Stan Rolfe

Fatigue: Limit state of crack initiation and growth resulting from repeated application of live loads



AISC 360-16

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CORROSION FATIGUE

Not covered in this presentation



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FATIGUE

Behavior:

Fatigue damage only occurs in regions that deform plastically under repeated fluctuating loads.

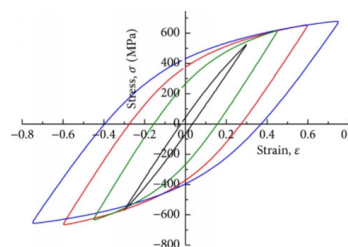
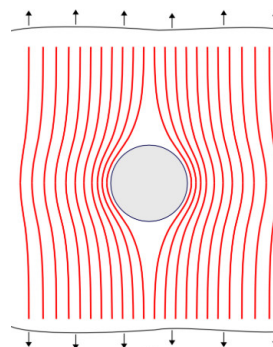


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FATIGUE BEHAVIOR

In an elastically loaded member stress risers create localized regions of plastic stress

Under repeated fluctuating load a hysteresis loop behavior occurs in the localized region.

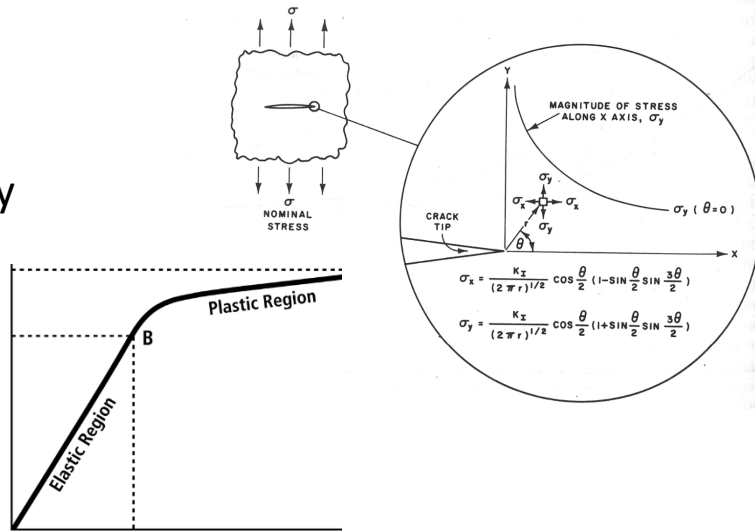


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FATIGUE BEHAVIOR

“Stress riser”

- Surface discontinuity
- Weld flaw
- Hole
- Shape or geometry

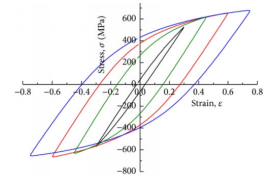


FATIGUE BEHAVIOR

Under repeated load applications the plastic strain advances until the material separates and the crack advances. Then the plastic stress region moves to the end of the larger crack and the process repeats.

Eventually:

Crack size and applied stress exceed the toughness of the material and fracture occurs.

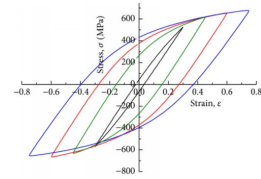


FATIGUE BEHAVIOR

Fatigue damage occurs in 3 stages:

- Crack initiation
- Crack propagation (Stable crack growth)
- Unstable crack growth to fracture

Crack initiation takes approximately 80% of the fatigue life of a structure.



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FATIGUE BEHAVIOR

Factors affecting fatigue performance: Material/Part

1. Geometry of the stress riser
2. Residual stresses
3. Steel and weld material properties
4. Temperature
5. Corrosion



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FATIGUE BEHAVIOR, TEMPERATURE

At temperatures up to 500 degrees F. crack growth rates are essentially the same as at room temperature.

Fatigue tests at -100 degrees F. indicate no observed change in crack growth rates.

Note: Brittle fracture is a greater concern at lower temperature.



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FATIGUE BEHAVIOR, STEEL MATERIAL PROPERTIES

Structural Steels with a specified minimum yield stress in the range of 36 to 100 ksi do not exhibit significantly different fatigue strengths.



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FATIGUE BEHAVIOR, RESIDUAL STRESSES

All welding processes result in high residual stresses at or near the yield point in the weldment and the adjacent weld metal. Therefore, the effect of residual stresses can be treated consistently in welded joints.

Fatigue cracks may initiate in regions of high tensile residual stress in elements of members subject solely to calculated compressive stress.

In such situations, the cracks generally do not propagate beyond the region of the residual tensile stress.



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FATIGUE BEHAVIOR

Factors affecting fatigue performance: Material/Part

1. Geometry of the stress riser “notch severity”
2. Residual stresses
3. Steel and weld material properties
4. Temperature
5. Corrosion

The severity of the stress riser is the dominant component factor for calculating fatigue life



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FATIGUE BEHAVIOR

Factors affecting fatigue performance: Load / Stress

1. Stress range
2. Maximum stress
3. State of stress



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FATIGUE BEHAVIOR, STRESS

State of Stress (Tension or Compression):

- Fluctuations in stress that does not involve tensile stress does not cause crack propagation and is not considered to be a fatigue situation.
- For this reason, stress ranges completely in compression need not be investigated for fatigue.



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FATIGUE BEHAVIOR, STRESS

Maximum stress:

- Other limit states and serviceability will often limit the maximum peak cyclic stress to below the yield stress. However, this condition must be confirmed.
- The maximum peak cyclic stress must remain in the elastic range or low cycle fatigue may occur.



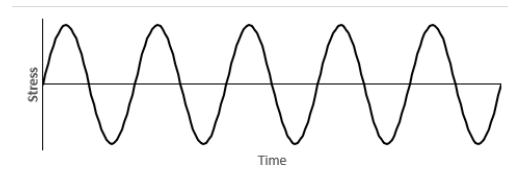
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FATIGUE BEHAVIOR, STRESS

Stress range (amplitude) is the difference between the maximum stress and the minimum stress.

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min}$$

Stress range is the dominant stress related factor for calculating fatigue life.

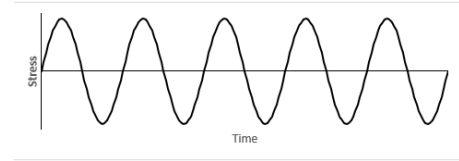


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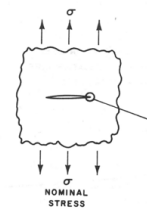
FATIGUE : CRITICAL VARIABLES

The two most significant variables that impact fatigue life calculations are:

1. Stress range
2. Stress risers or notch severity



These two factors have the greatest impact on the magnitude of stress or strain in the localized region of the stress riser.



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FATIGUE LIFE:

Methods of evaluation

- S N curves (traditional approach)
 - Statistically developed curves that plot stress amplitude (S) vs. cycles to failure (N)
- Fracture mechanics approach
 - Fatigue crack initiation, propagation, and unstable crack propagation (final fracture).



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SN CURVES

Tests were performed for different categories of details and different SN curves have been developed for these categories of details.

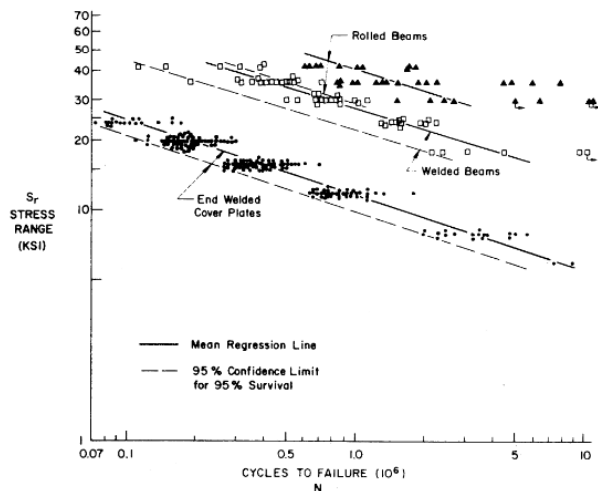


Fig. 3. Fatigue strength of rolled, welded, and coverplated beams

Fisher, John W. and Yen, Ben T. (1977), "Fatigue Strength of Steel Members with Welded Details" *AISC Engineering Journal*.

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Stress Categories (research basis):

- A Rolled Beams
- B Longitudinal stiffeners and flange splices
- C Stiffeners and short 2" attachments
- D Longer attachments (4")
- E Cover plated beams



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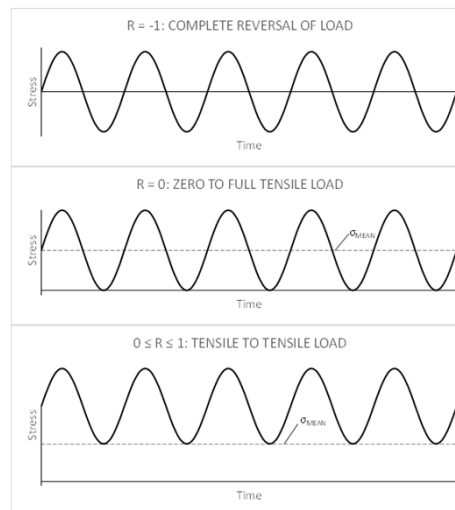
FATIGUE BEHAVIOR, EVALUATION

Fatigue Limit

Steel has a “fatigue limit”

The fatigue limit is the stress range at which an unlimited number of cycles can be applied without failure.

For polished steel, this limit is about 50% of the tensile strength of the steel.



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AISC 360-16 APPENDIX 3

3.1 GENERAL PROVISIONS

3.2 CALCULATION OF MAXIMUM STRESSES AND STRESS RANGES

3.3 PLAIN MATERIAL AND WELDED JOINTS

3.4 BOLTS AND THREADED PARTS

3.5 FABRICATION AND ERECTION REQUIREMENTS FOR FATIGUE

3.6 NONDESTRUCTIVE EXAMINATION REQUIREMENTS FOR FATIGUE



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FATIGUE: AISC 360

3.1 GENERAL PROVISIONS (SCOPE):

- High cycle fatigue in situations where the primary member cyclic stresses are in the elastic range.
- Number of full cycles exceeds 20,000 (or equivalent)
- Limited to structures with corrosion protection or subject to only mildly corrosive atmospheres.



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FATIGUE, AISC 360

3.1 GENERAL PROVISIONS (SCOPE):

- The maximum temperature for application of the Appendix is 300 degrees F.
- The maximum permitted stress due to peak cyclic loads is $.66F_y$



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3.2 CALCULATION OF MAXIMUM STRESSES AND STRESS RANGES

Calculate applied unfactored live load stresses based on elastic analysis (not amplified for stress concentration factors)

$$M_u \leq \phi M_n \quad P_u \leq \phi P_n$$

$$f_b = M/S_x \quad f_a = P/A$$

For bolts and threaded rods the calculated tension stress shall include prying (if any).



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3.2 CALCULATION OF MAXIMUM STRESSES AND STRESS RANGES

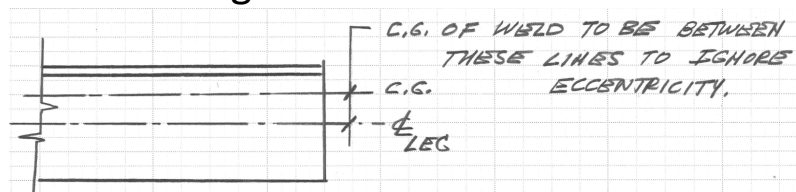
For members having symmetric cross sections, the fasteners and welds shall be arranged symmetrically about the axis of the member, or the total stresses including those due to eccentricity shall be included in the calculation of the stress range.



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3.2 CALCULATION OF MAXIMUM STRESSES AND STRESS RANGES

For axially loaded angles where the center of gravity of the connecting welds lies between the center of gravity of the angle and the center of the connected leg eccentricity shall be ignored. If not stresses due to eccentricity shall be included in the calculated stress range.



3.3 PLAIN MATERIAL AND WELDED JOINTS

The Appendix relies on a series of S-N curves that predict the number of load cycles that can be safely resisted for a given category (stress riser configuration).

The resistance curves are set two standard deviations below the mean test result for a given category.

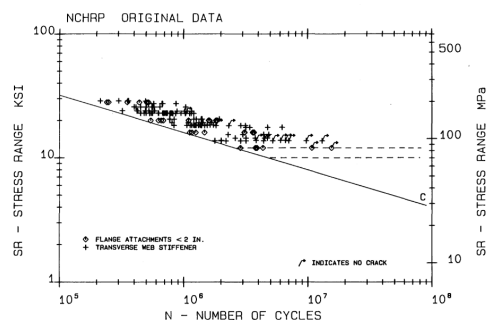


Figure 6 Fatigue Resistance of Category C Details, Original Database



3.3 PLAIN MATERIAL AND WELDED JOINTS

Stress Categories

A, B, B', C, D, E, E', and G

As defined in Table A-3.1

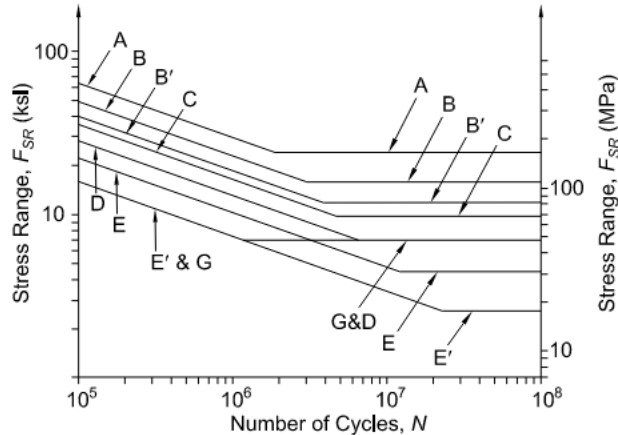


Fig. C-A-3.1. Fatigue resistance curves.



3.3 PLAIN MATERIAL AND WELDED JOINTS

Stress Categories:

F Welds loaded in shear

C' PJP groove welds loaded transverse to the direction of stress

C'' Fillet welds loaded transverse to the direction of stress

As defined in Table A-3.1

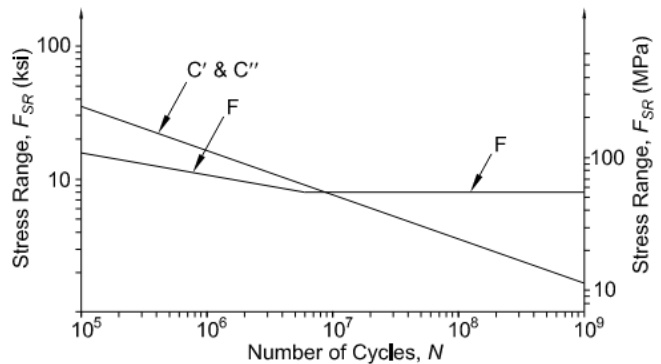


Fig. C-A-3.2. Fatigue resistance curves for stress categories C and F.



3.3 PLAIN MATERIAL AND WELDED JOINTS (a)

Categories A, B, B', C, D, E, E'

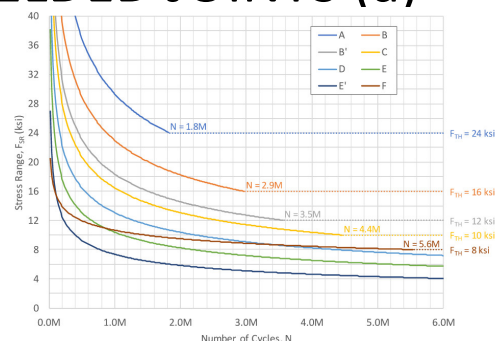
$$F_{SR} = 1000 \left(\frac{C_f}{n_{SR}} \right)^{.333} \geq F_{TH} \quad (A-3-1)$$

F_{SR} = allowable stress range (ksi)

C_f = constant from Table A-3.1 for the fatigue category

n_{SR} = number of stress range fluctuations in design life

F_{TH} = threshold allowable stress range (ksi), max. stress range for infinite design life (Table A-3.1)



Stress Categories, TABLE A-3.1

8 SECTIONS (GENERAL CONDITIONS OF FATIGUE)

- 1- PLAIN MATERIAL AWAY FROM ANY WELDING (A, B, C, D, E')
- 2- CONNECTED MATERIAL IN MECHANICALLY FASTENED JOINTS (B, C, E)
- 3- WELDED JOINTS JOINING COMPONENTS OF BUILT-UP MEMBERS (B, B', D, E, E')
- 4- LONGITUDINAL FILLET WELDED END CONNECTIONS (E, E')
- 5- WELDED JOINTS TRANSVERSE TO DIRECTION OF STRESS (B, B', C, C', C'', D, E)
- 6- BASE METAL AT WELDED TRANSVERSE MEMBER CONNECTIONS (B, C, D, E)
- 7- BASE MATERIAL AT SHORT ATTACHMENTS (C, D, E, E')
- 8- MISCELLANEOUS (C, E, F, G)



TABLE A-3.12 1. PLAIN MATERIAL AWAY FROM ANY WELDING

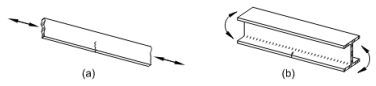
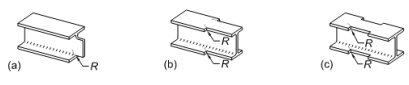

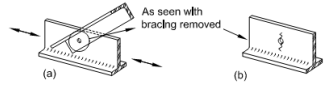



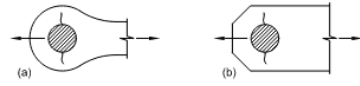
Description	Stress Category	Constant C_f	Threshold F_{TH} ksi (MPa)	Potential Crack Initiation Point	Illustrative Typical Examples
SECTION 1—PLAIN MATERIAL AWAY FROM ANY WELDING					SECTION 1—PLAIN MATERIAL AWAY FROM ANY WELDING
1.1 Base metal, except noncoated weathering steel, with as-rolled or cleaned surfaces; flame-cut edges with surface roughness value of 1,000 μ m (25 μ m) or less, but without reentrant corners	A	25	24 (165)	Away from all welds or structural connections	1.1 and 1.2 
1.2 Noncoated weathering steel base metal with as-rolled or cleaned surfaces; flame-cut edges with surface roughness value of 1,000 μ m (25 μ m) or less, but without reentrant corners	B	12	16 (110)	Away from all welds or structural connections	
1.3 Member with reentrant corners at copes, cuts, block-outs or other geometrical discontinuities, except weld access holes $R \geq 1$ in. (25 mm), with radius, R , formed by predrilling, subpunching and reaming or thermally cut and ground to a bright metal surface $R \geq 3/8$ in. (10 mm) and the radius, R , need not be ground to a bright metal surface	C E'	4.4 0.39	10 (69) 2.6 (18)	At any external edge or at hole perimeter	1.3 
1.4 Rolled cross sections with weld access holes made to requirements of Section J1.6 Access hole $R \geq 1$ in. (25 mm) with radius, R , formed by predrilling, subpunching and reaming or thermally cut and ground to a bright metal surface Access hole $R \geq 3/8$ in. (10 mm) and the radius, R , need not be ground to a bright metal surface	C E'	4.4 0.39	10 (69) 2.6 (18)	At reentrant corner of weld access hole	1.4 
1.5 Members with drilled or reamed holes Holes containing pretensioned bolts Open holes without bolts	C D	4.4 2.2	10 (69) 7 (48)	In net section originating at side of the hole	1.5 



TABLE A-3.12 2. CONNECTED MATERIAL IN MECHANICALLY FASTENED JOINTS

Description	Stress Category	Constant C_f	Threshold F_{TH} ksi (MPa)	Potential Crack Initiation Point	Illustrative Typical Examples
SECTION 2—CONNECTED MATERIAL IN MECHANICALLY FASTENED JOINTS					SECTION 2—CONNECTED MATERIAL IN MECHANICALLY FASTENED JOINTS
2.1 Gross area of base metal in lap joints connected by high-strength bolts in joints satisfying all requirements for slip-critical connections	B	12	16 (110)	Through gross section near hole	2.1  (Note: Figures are for slip-critical bolted connections.)
2.2 Base metal at net section of high-strength bolted joints, designed on the basis of bearing resistance, but fabricated and installed to all requirements for slip-critical connections	B	12	16 (110)	In net section originating at side of hole	2.2  (Note: Figures are for bolted connections designed to bear, meeting the requirements of slip-critical connections.)
2.3 Base metal at the net section of riveted joints	C	4.4	10 (69)	In net section originating at side of hole	2.3  (Note: Figures are for snug-tightened bolts, rivets, or other mechanical fasteners.)
2.4 Base metal at net section of eyebolt head or pin plate	E	1.1	4.5 (31)	In net section originating at side of hole	2.4 



3.3 PLAIN MATERIAL AND WELDED JOINTS (b)

Category F

$$F_{SR} = 100(1.5/n_{SR})^{.167} \geq 8 \text{ ksi} \quad (\text{A-3-2})$$

F_{SR} = allowable stress range (ksi)

1.5 in place of C_f

n_{SR} = number of stress range fluctuations in design life

$$F_{TH} = 8 \text{ ksi}$$

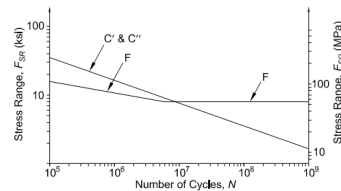


Fig. C-A-3.2. Fatigue resistance curves for stress categories C and F.

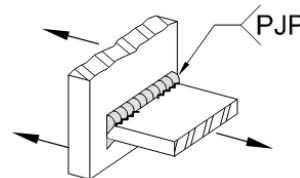


3.3 PLAIN MATERIAL AND WELDED JOINTS (c)

Transverse loaded PJP groove welds

Check two conditions.

1. Crack initiation at the toe of the weld
2. Crack initiation at the root of the weld



Check crack initiation at the weld toe per stress category C

Check crack initiation at the weld root per stress category C'

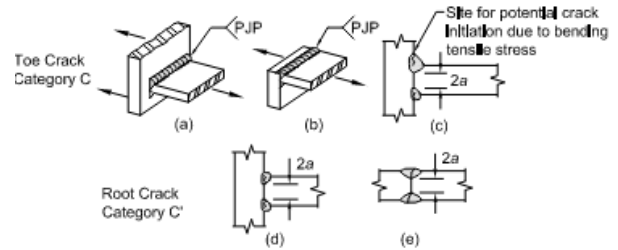


3.3 PLAIN MATERIAL AND WELDED JOINTS

Category C'

$$F_{SR} = 1,000 R_{PJP} \left(\frac{4.4}{n_{SR}} \right)^{.333} \quad (A-3-3)$$

$$R_{PJP} = \frac{0.65 - .059 \left(\frac{2a}{t_p} \right) + .72 \left(\frac{w}{t_p} \right)}{t_p^{.167}} \leq 1.0 \quad (A-3-4)$$



R_{PJP} is the stress reduction factor for reinforced or unreinforced PJP groove welds. If $R_{PJP} = 1$ stress category C will control.

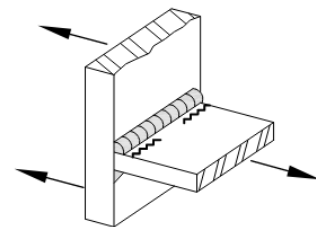


3.3 PLAIN MATERIAL AND WELDED JOINTS

Transverse loaded Fillet welds

Check two conditions.

1. Crack initiation at the toe of the weld
2. Crack initiation at the root of the weld



Check crack initiation at the weld toe per stress category C

Check crack initiation at the weld toe per stress category C''



3.3 PLAIN MATERIAL AND WELDED JOINTS

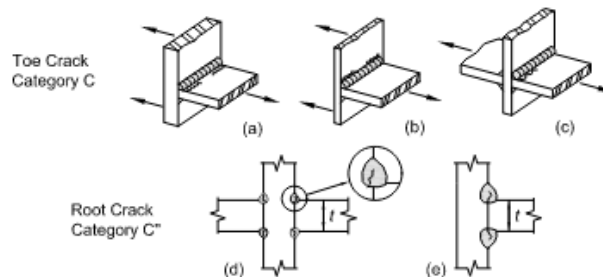
Category C''

$$F_{SR} = 1,000 R_{FIL} \left(\frac{4.4}{n_{SR}} \right)^{.333} \quad (A-3-5)$$

$$R_{FIL} = \frac{0.06 + 72 \left(\frac{w}{t_p} \right)}{t_p^{.167}} \leq 1.0 \quad (A-3-6)$$

R_{FIL} is the stress reduction factor for joints using a pair of transverse fillet welds.

If $R_{FIL} = 1$ stress category C will control.



3.4 BOLTS AND THREADED PARTS

Mechanically fastened Connections in Shear

Limit the maximum range of stress in the connection material to the allowable stress range computed using Equation A-3-1

$$F_{SR} = 1000 \left(\frac{C_f}{n_{SR}} \right)^{.333} \geq F_{TH} \quad (A-3-1)$$

C_f and F_{TH} are taken from section 2 of Table A-3.1



3.4 BOLTS AND THREADED PARTS

Mechanically fastened Connections in Shear

Limit the maximum range of stress in the connection material to the allowable stress range computed using Equation A-3-1

$$F_{SR} = 1000 \left(\frac{C_f}{n_{SR}} \right)^{.333} \geq F_{TH} \quad (A-3-1)$$

C_f and F_{TH} are taken from section 2 of Table A-3.1

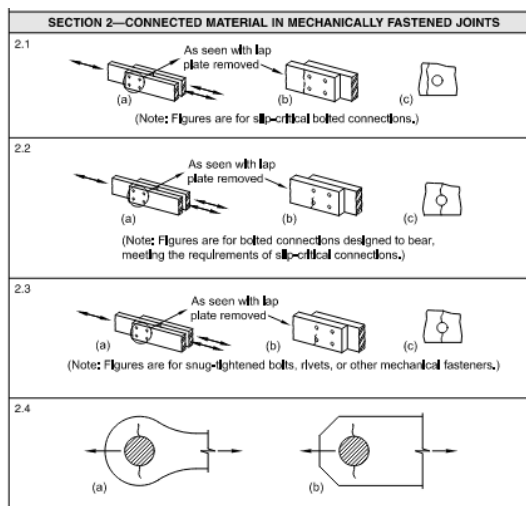


3.4 BOLTS AND THREADED PARTS

Base metal at fasteners in Shear:

Connections must be constructed as slip critical (slip critical design is recommended.)

The bolts (properly sized) will not control fatigue life compared the connected material.



3.4 BOLTS AND THREADED PARTS

Fasteners in Tension:

High strength bolts , common bolts, threaded anchor rods, hanger rods.

Limit the maximum range of tensile stress on the net tensile area from the applied load plus load due to prying action to the allowable stress range computed using equation A-3-1

C_f and F_{TH} are taken from Case 8.5 of Table A-3.1 (Stress category G)



3.4 BOLTS AND THREADED PARTS

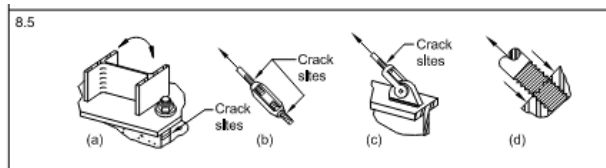
Note (tension fasteners):

$$A_t = \frac{\pi}{4} \left(d_b - \frac{.9743}{n} \right)^2$$

d_b = nominal bolt diameter

n = threads per inch (table 7-17 page 7-83)

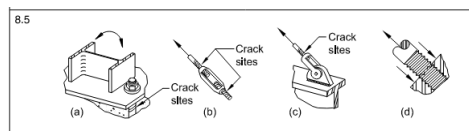
8.5 High-strength bolts, common bolts, threaded anchor rods, and hanger rods, whether pretensioned in accordance with Table J3.1 or J3.1M, or snug-tightened with cut, ground or rolled threads; stress range on tensile stress area due to applied cyclic load plus prying action, when applicable	G	0.39	7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



3.4 BOLTS AND THREADED PARTS

Note (tension fasteners):

If material in the grip is not limited to steel or not tensioned to Table J3.1 all axial load and moment applied to the joint plus prying shall be assumed to be carried exclusively by the bolts.



3.4 BOLTS AND THREADED PARTS

Note (tension fasteners):

If material in the grip is limited to steel and is pretensioned to Table J3.1 an analysis of the connected parts and bolts is permitted to determine the tensile stress range in the pretensioned bolts due to the cyclic load (plus prying). Alternatively the stress range in the bolts shall be assumed equal to the stress on the net tensile area due to 20% of the absolute value of the of the applied cyclic load.



3.4 BOLTS AND THREADED PARTS

Note (tension fasteners):

- Refer to Design Guide 17 *High Strength Bolts: A Primer for Structural Engineers* (Kulak, 2002) for a further information (www.aisc.org/dg)



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15th ed. AISC Manual Section 16.2

Specification for Structural Joints Using High-Strength Bolts

August 1, 2014
(includes April 2015 Errata)

“RCSC Bolt Spec”

- Manual
- AISC Free download



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Specification for Structural Joints Using High Strength Bolts

Table 5.2. Maximum Tensile Stress for Fatigue Loading

Number of Cycles	Maximum Bolt Stress for Design at Service Loads ^a , ksi	
	ASTM A325 or F1852	ASTM A490 or F2280
Not more than 20,000	45	57
From 20,000 to 500,000	40	49
More than 500,000	31	38

^a Including the effects of *prying action*, if any, but excluding the pretension.

CHECK MAXIMUM STRESS ON THE NOMINAL BOLT DIAMETER
LIMIT PRYING FORCES TO 30% OF THE EXTERNALLY APPLIED LOAD



3.5 FABRICATION AND ERECTION REQUIREMENTS FOR FATIGUE

Welding:

- Longitudinal backing shall be continuous
 - Splice backing with CJP groove welds grind flush for tight fit
 - Fillet welds connecting left in place backing shall be continuous.
- In transverse CJP groove welded T and corner joints a reinforcing fillet weld not less than ¼" shall be added at reentrant corners.



3.5 FABRICATION AND ERECTION REQUIREMENTS FOR FATIGUE

Cutting:

The surface roughness of thermally cut edges subject to cyclic stress ranges, that include tension shall not exceed 1,000 μin ...

Reentrant corners at cuts, copes, and welds access holes shall form a radius not less than the prescribed radius in Table A-3.1 by predrilling or subpunching and reaming a hole or by thermal cutting to form the radius of the cut.



3.5 FABRICATION AND ERECTION REQUIREMENTS FOR FATIGUE

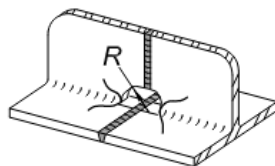


TABLE A-3.1
Fatigue Design Parameters

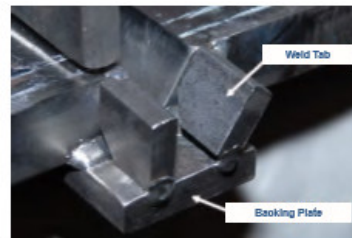
Description	Stress Category	Constant C_f	Threshold F_{TH} ksi (MPa)	Potential Crack Initiation Point
SECTION 1—PLAIN MATERIAL AWAY FROM ANY WELDING				
1.4 Rolled cross sections with weld access holes made to requirements of Section J1.6				At reentrant corner of weld access hole
Access hole $R \geq 1$ in. (25 mm) with radius, R , formed by predrilling, subpunching and reaming or thermally cut and ground to a bright metal surface	C	4.4	10 (69)	
Access hole $R \geq 3/8$ in. (10 mm) and the radius, R , need not be ground to a bright metal surface	E'	0.39	2.6 (18)	



3.5 FABRICATION AND ERECTION REQUIREMENTS FOR FATIGUE

Welding:

Transverse butt joints in regions of tensile stress, weld tabs shall be used ... End dams shall not be used. Weld tabs shall be removed, and the end of the weld finished flush with the edge of the member.



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3.5 FABRICATION AND ERECTION REQUIREMENTS FOR FATIGUE

Welding:

Fillet welds subjected to cyclic loading normal to the outstanding legs of the angles or on the outer edges of end plates shall have end returns around the corner for a distance not less than two times the weld size; end return distance shall not exceed four times the weld size.



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3.6 NONDESTRUCTIVE EXAMINATION REQUIREMENTS FOR FATIGUE

In the case of CJP groove welds, the maximum allowable stress range calculated by Equation A-3-1 applies only to welds that have been ultrasonically or radiographically tested and meet the requirements of *Structural Welding Code-Steel* (AWS D1.1:2015) clause 6.12.2 or clause 6.13.2

Note: Refer to Chapter N for typical inspection requirements.



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FABRICATION AND INSPECTION REQUIREMENTS: AWS

Specify in the contract documents if the structure (or which part of the structure) is cyclically loaded.

Refer to *Structural Welding Code-Steel* (AWS D1.1:2015)

- Clause 1. General Requirements
- Clause 8. Inspection, Part C Acceptance Criteria.



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EXAMPLES

Crane Girder Example
Bolted Connection Example

Additional fatigue calculation examples can be found in the CISC Design Guide.

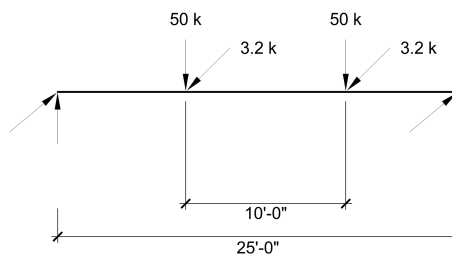


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CRANE GIRDER EXAMPLE

Crane support beam:

- Span= 25 feet (simple span)
- Crane Capacity =30 tons
- Wheel Spacing = 10 feet.
- Impact Factor = 25 %
- Lateral Load = 3.2 kips /wheel
- Maximum Wheel Load = 50 kips (without impact)
- Minimum Wheel Load = 25 kips (without impact)
- 1,000,000 cycles



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CRANE GIRDER EXAMPLE

Crane support beam, service level moments and shears:

AIST DG#13 nomenclature and load combination for fatigue

- C_{ds} = crane dead load for a single crane
- C_{vs} = vertical single crane lifted load
- C_{ss} = crane side thrust from a single crane

Load combination for fatigue: $C_{ds} + C_{vs} + (1/2) C_{ss}$ (excludes impact)

M_{ds+vs} = 400 ft-kip (without impact) (strong axis moment)

M_{ss} = 31.2 ft-kip (100 % lateral load) (weak axis moment, top flange)

M_D = 20 ft-kip (strong axis moment)



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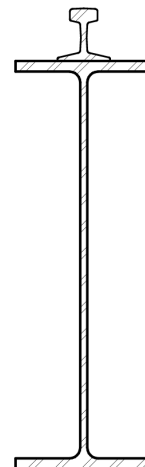
CRANE GIRDER EXAMPLE

Selected Girder: W27x146

S_x = 414 in³

S_{ytop} = 32 in³ (top flange only)

Checking the cross section for other limit states such as bending, shear, deflection, sidesway web buckling are not included in this example.



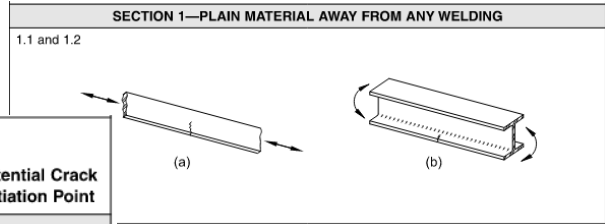
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CRANE GIRDER EXAMPLE

Check fatigue at the bottom flange

Stress Category A:

Description	Stress Category	Constant C_f	Threshold F_{TH} ksi (MPa)	Potential Crack Initiation Point
SECTION 1—PLAIN MATERIAL AWAY FROM ANY WELDING				
1.1 Base metal, except noncoated weathering steel, with as-rolled or cleaned surfaces; flame-cut edges with surface roughness value of 1,000 μ in. (25 μ m) or less, but without reentrant corners	A	25	24 (165)	Away from all welds or structural connections



$C_f = 25 \quad F_{TH} = 24 \text{ ksi}$

Equation A-3-1 $F_{SR} = 1000 \left(\frac{C_f}{n_{SR}} \right)^{.333} = 1000 \left(\frac{25}{1,000,000} \right)^{.333} = 29.3 \text{ ksi} > 24.0 \text{ ksi}$



CRANE GIRDER EXAMPLE

Check fatigue at the bottom flange:

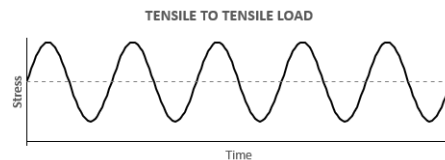
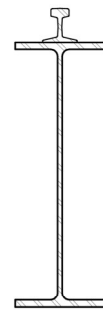
$f_{b \text{ dl}} = \frac{M_{dl}}{S_{xbot}} = \frac{20 \times 12}{414} = 0.6 \text{ ksi}$ $f_{b \text{ ds+vs}} = \frac{M_{ds+vs}}{S_{xbot}} = \frac{400 \times 12}{414} = 11.6 \text{ ksi}$

Check peak cyclic stress:

$F_{b \text{ max}} = .6 + 11.6 = 12.2 \text{ ksi} < .66F_y = 33 \text{ ksi} \quad \text{OK.}$

Check stress range:

$f_{SR} = 11.6 \text{ ksi} < F_{SR} = 29.3 \text{ ksi} \quad \text{OK.}$



CRANE GIRDER EXAMPLE

Fatigue at the top flange, confirm top flange remains in compression:

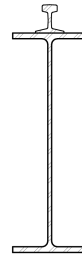
$$f_{by\ ss/2} = \frac{M_{ss/2}}{S_{ytop}} = \frac{31.2 \times 12 / 2}{32} = +/- 5.9 \text{ ksi}$$

$$f_{bx\max\ ds+vs} = \frac{M_D + M_{ds+vs}}{S_{xtop}} = \frac{420 \times 12}{414} = -12.2 \text{ ksi}$$

$$f_{bx\min\ ds+vs} = \frac{M_D + (25/50)M_{ds+vs}}{S_{xtop}} = \frac{220 \times 12}{414} = -6.4 \text{ ksi}$$

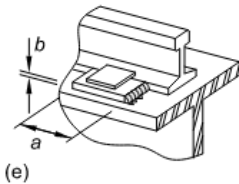
Minimum compressive stress = $(-6.4 + 5.9) = -0.5 \text{ ksi}$

Maximum compressive stress = $(-12.2 - 5.9) = -18.1 \text{ ksi}$ SAY OK



CRANE GIRDER EXAMPLE

fatigue at the top flange:



$$C_f = 2.2 \quad F_{TH} = 7 \text{ ksi}$$

$$F_{sr} = 1000 \left(\frac{C_f}{n_{SR}} \right)^{.333} = 1000 \left(\frac{2.2}{1,000,000} \right)^{.333} = 13.1 \text{ ksi.}$$

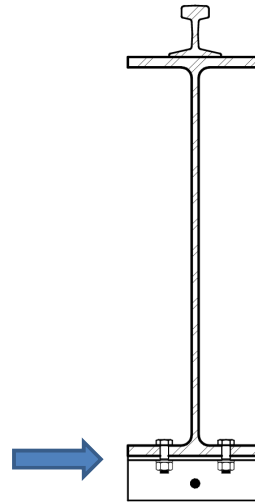
Description	Stress Category	Constant C_f	Threshold F_{TH} , ksi (MPa)	Potential Crack Initiation Point
SECTION 7—BASE METAL AT SHORT ATTACHMENTS^(a)				
7.1 Base metal subject to longitudinal loading at details with welds parallel or transverse to the direction of stress, with or without transverse load on the detail, where the detail embodies no transition radius, R , and with detail length, a , and thickness of the attachment, b :				Initiating in base metal at the weld termination or at the toe of the weld extending into the base metal
$a < 2 \text{ in. (50 mm)}$ for any thickness, b	C	4.4	10 (69)	
$2 \text{ in. (50 mm)} \leq a \leq$ lesser of $12b$ or 4 in. (100 mm)	D	2.2	7 (48)	
$a >$ lesser of $12b$ or 4 in. (100 mm) when $b \leq 0.8 \text{ in. (20 mm)}$	E	1.1	4.5 (31)	
$a > 4 \text{ in. (100 mm)}$ when $b > 0.8 \text{ in. (20 mm)}$	E'	0.39	2.6 (18)	



CRANE GIRDER EXAMPLE

Check fatigue at a field added modification that consists of a pipe hanger bolted to the bottom flange.

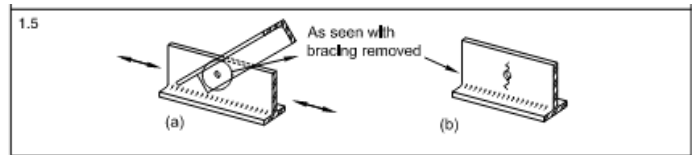
The load from the pipe hanger is not significant and is not cyclical. However, this changes the stress category at the bottom flange.



CRANE GIRDER EXAMPLE

Check fatigue at the bottom flange bolted pipe hanger:
 With Pretensioned bolts in the holes.

$$f_{SR} = \frac{M_{ds+vs}}{S_{xbot}} = \frac{400 \times 12}{371} = 11.6 \text{ ksi}$$



1.5 Members with drilled or reamed holes				In net section originating at side of the hole
Holes containing pretensioned bolts	C	4.4	10 (69)	
Open holes without bolts	D	2.2	7 (48)	

$$F_{sr} = 1000 \left(\frac{C_f}{n_{SR}} \right)^{.333} = 1000 \left(\frac{4.4}{1,000,000} \right)^{.333} = 16.5 \text{ ksi. OK}$$



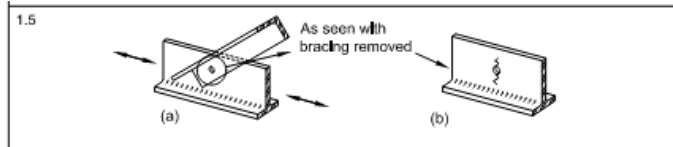
CRANE GIRDER EXAMPLE

Check fatigue at the bottom flange bolted pipe hanger:

Hanger is removed no bolts in the holes.



$$f_{SR} = \frac{M_{ds+vs}}{S_{xbot}} = \frac{400 \times 12}{414} = -11.6 \text{ ksi}$$



1.5 Members with drilled or reamed holes				In net section originating at side of the hole
Holes containing pretensioned bolts	C	4.4	10 (69)	
Open holes without bolts	D	2.2	7 (48)	

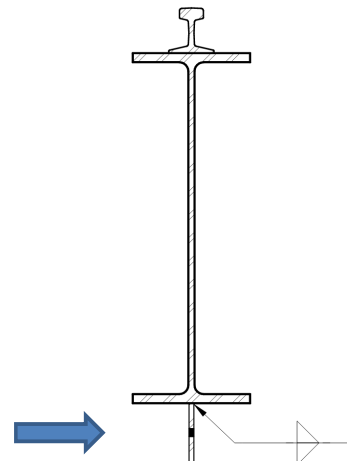
$$F_{SR} = 1000 \left(\frac{C_f}{n_{SR}} \right)^{.333} = 1000 \left(\frac{2.2}{1,000,000} \right)^{.333} = 13.1 \text{ ksi. OK}$$



CRANE GIRDER EXAMPLE

Check fatigue at a field added modification that consists of a pipe hanger welded to the bottom flange.

The load from the pipe hanger is not significant and is not cyclical. However, this changes the stress category at the bottom flange.



CRANE GIRDER EXAMPLE

Check the bottom flange welded pipe hanger: welded angle hanger plate:

SECTION 7—BASE METAL AT SHORT ATTACHMENTS ^[a]		SECTION 7—BASE METAL AT SHORT ATTACHMENTS ^[a]			
7.1 	7.1 Base metal subject to longitudinal loading at details with welds parallel or transverse to the direction of stress, with or without transverse load on the detail, where the detail embodies no transition radius, R , and with detail length, a , and thickness of the attachment, b : $a < 2$ in. (50 mm) for any thickness, b 2 in. (50 mm) $\leq a \leq$ lesser of $12b$ or 4 in. (100 mm) $a >$ lesser of $12b$ or 4 in. (100 mm) when $b \leq 0.8$ in. (20 mm) $a > 4$ in. (100 mm) when $b > 0.8$ in. (20 mm)				Initiating in base metal at the weld termination or at the toe of the weld extending into the base metal
		C	4.4	10 (69)	
		D	2.2	7 (48)	
		E	1.1	4.5 (31)	
		E'	0.39	2.6 (18)	
[a] "Attachment," as used herein, is defined as any steel detail welded to a member that causes a deviation in the stress flow in the member and, thus, reduces the fatigue resistance. The reduction is due to the presence of the attachment, not due to the loading on the attachment.					

CRANE GIRDER EXAMPLE

Check fatigue at the bottom flange welded pipe hanger: welded hanger :

Stress Category D

$$C_f = 2.2 \quad F_{TH} = 7.0 \text{ ksi}$$

$$f_{SR} = 11.6 \text{ ksi} < F_{SR} = 1000 \left(\frac{C_f}{n_{SR}} \right)^{.333} = 1000 \left(\frac{2.2}{1,000,000} \right)^{.333} = 13.1 \text{ ksi.} \quad \text{OK}$$

Stress Category E

$$C_f = 1.1 \quad F_{TH} = 4.5 \text{ ksi}$$

$$f_{SR} = 11.6 \text{ ksi} > F_{SR} = 1000 \left(\frac{C_f}{n_{SR}} \right)^{.333} = 1000 \left(\frac{1.1}{1,000,000} \right)^{.333} = 10.4 \text{ ksi.} \quad \text{NG}$$

Solving for n_{SR} at $F_{SR} = 11.6$ ksi yields 705,000 cycles

WELDED CRANE GIRDER

Refer to AISC DG #13 for heavy duty fabrication requirements:

Web and flange splices to be CJP welds, ground flush, with the grinding direction parallel to the span. Stagger flange and web splice locations.

Top flange to web weld to be CJP with contoured fillets. (Refer to AISC Manual table 8-2)

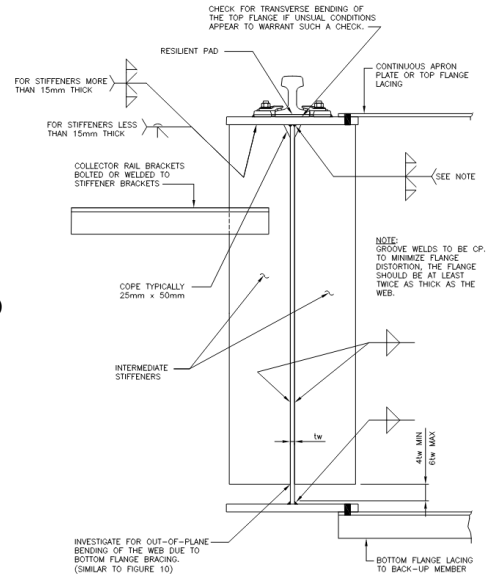


Figure 19
 Typical Heavy-Duty Crane Runway Beam

Figure: Crane Supporting Steel Structures third Ed. CISC

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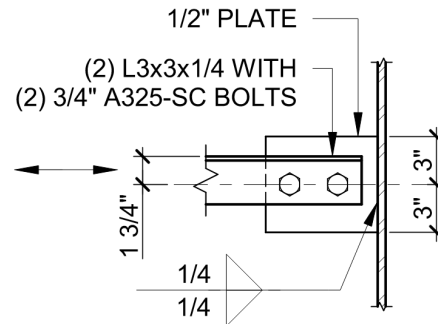
BOLTED CONNECTION EXAMPLE

- (2) L3x3x1/4 (50 ksi angle and Plate)
- Cyclic live load +/-10 kips
- 500,000 cycles

Angle Properties

$$A=2 \times 1.44 \text{ in}^2 \quad I=2 \times 1.23 \text{ in}^4 \quad \bar{y}_{\text{bar}}=.836''$$

$$\text{Moment due to eccentricity of the connection} = 10^k(1.75'' - .836'') = 9.14 \text{ k-in}$$



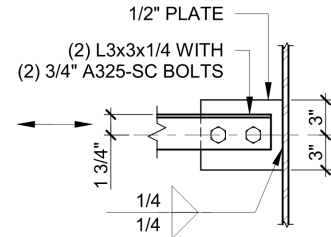
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BOLTED CONNECTION EXAMPLE

Check the angles:

Tension causes compression at the angle heel and tension in the angle toe.

Compression causes tension at the angle heel and compression in the angle toe.



$$\text{Max stress} = (f_a + f_b) = \frac{10}{2 \cdot 1.44} + \frac{9.14(3 - 0.836)}{2(1.23)} = 3.5 + 8.0 = 11.5 \text{ ksi} < .66(50) \text{ ksi OK}$$

$$f_{SR} = 2(f_a + f_b) = 2(3.5 + 8.0) = 23.0 \text{ ksi}$$



BOLTED CONNECTION EXAMPLE

Stress Category B

$$C_f = 12 \quad F_{TH} = 16 \text{ ksi}$$

$$F_{SR} = 1000 \left(\frac{C_f}{n_{SR}} \right)^{.333} = 1000 \left(\frac{12}{500,000} \right)^{.333} = 28.9 \text{ ksi.}$$

$$F_{SR} = 28.9 \text{ ksi} > 23.0 \text{ ksi} \quad \text{Angles OK}$$

Illustrative Typical Examples				
SECTION 2—CONNECTED MATERIAL IN MECHANICALLY FASTENED JOINTS				
2.1	<p>(Note: Figures are for slip-critical bolted connections.)</p>			
TABLE A-3.1 (continued) Fatigue Design Parameters				
Description	Stress Category	Constant C_f	Threshold F_{TH} ksi (MPa)	Potential Crack Initiation Point
SECTION 2—CONNECTED MATERIAL IN MECHANICALLY FASTENED JOINTS				
2.1 Gross area of base metal in lap joints connected by high-strength bolts in joints satisfying all requirements for slip-critical connections	B	12	16 (110)	Through gross section near hole



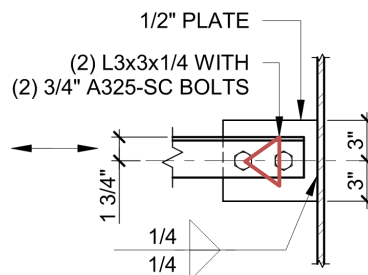
BOLTED CONNECTION EXAMPLE

Check the plate at the bolts:

The load is concentric on the plate and the weld

Stress Category B: $C_f=12$ $F_{TH}=16$ ksi

$$f_{SR}=2(f_a) = 2\left(\frac{10}{3.5 \times 5}\right) = 11.4 \text{ ksi} < F_{TH}=16 \text{ ksi} \quad \text{OK}$$



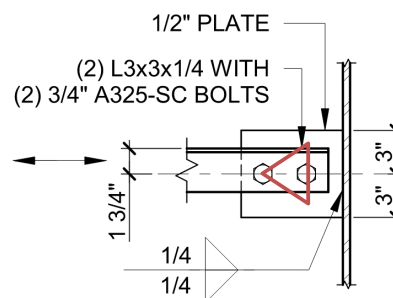
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BOLTED CONNECTION EXAMPLE

Check the plate at the fillet welds:

$$f_{SR}=2(f_a) = 2\left(\frac{10}{3.5 \times 5}\right) = 11.4 \text{ ksi}$$

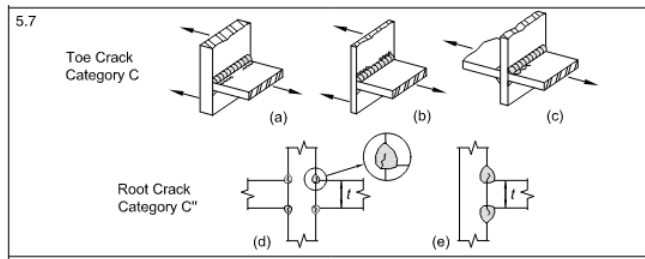
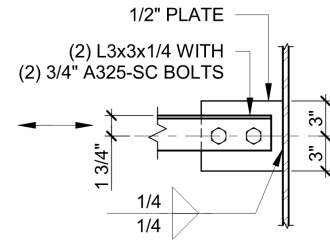
Crack initiation at the weld toe: Stress Category C
 Crack initiation at the weld root: Stress Category C''



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BOLTED CONNECTION EXAMPLE

5.7 Base metal and weld metal at transverse end connections of tension-loaded plate elements using a pair of fillet welds on opposite sides of the plate; F_{SR} shall be the smaller of the weld toe crack or weld root crack allowable stress range				
Crack initiating from weld toe	C	4.4	10 (69)	Initiating from weld toe extending into base metal
Crack initiating from weld root	C''	See Eq. A-3-5 or A-3-5M	None	Initiating at weld root extending into and through weld



BOLTED CONNECTION EXAMPLE

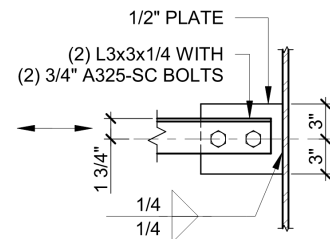
Check the plate at the fillet welds 3.3c(3):

$$f_{SR} = 2(f_a) = 2\left(\frac{10}{3.5 \times 5}\right) = 11.4 \text{ ksi}$$

Crack at the weld root

$$R_{FIL} = \frac{0.06 + 0.72\left(\frac{w}{t}\right)}{t_p^{0.167}} \leq 1.0 = \frac{.06 + 0.72\left(\frac{0.25}{0.5}\right)}{0.5^{0.167}} = 0.47$$

$$F_{SR} = 1000 R_{FIL} \left(\frac{4.4}{n_{SR}}\right)^{0.333} = 1000(.47)\left(\frac{4.4}{500,000}\right)^{0.333} = 9.7 \text{ ksi.} < 11.4 \text{ ksi NG}$$



BOLTED CONNECTION EXAMPLE

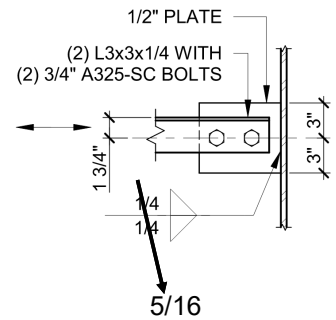
Try larger fillet weld (5/16")

$$f_{SR} = 2(f_a) = 2\left(\frac{10}{3.5 \times 5}\right) = 11.4 \text{ ksi}$$

Crack at the weld root

$$R_{FIL} = \frac{0.06 + 0.72\left(\frac{w}{t}\right)}{t_p^{0.167}} \leq 1.0 = \frac{.06 + 0.72\left(\frac{0.3125}{0.5}\right)}{0.5^{0.167}} = 0.57$$

$$F_{SR} = 1000 R_{FIL} \left(\frac{4.4}{n_{SR}}\right)^{0.333} = 1000(.57)\left(\frac{4.4}{500,000}\right)^{0.333} = 11.8 \text{ ksi} < 11.4 \text{ ksi OK}$$



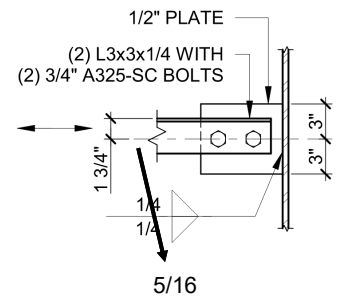
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BOLTED CONNECTION EXAMPLE

Crack at the weld toe:

Stress Category C: $C_f = 4.4$ $F_{TH} = 10 \text{ ksi}$

$$F_{SR} = 1000 \left(\frac{C_f}{n_{SR}}\right)^{.333} = 1000 \left(\frac{4.4}{500,000}\right)^{.333} = 20.7 \text{ ksi} > 11.4 \text{ ksi OK}$$



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STANDARDS & REFERENCES

AISC 360 **Appendix 3 FATIGUE**

FRACTURE & FATIGUE CONTROL IN STRUCTURES
Applications of Fracture Mechanics John Barsom & Stan
Rolfe



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STANDARDS & REFERENCES

Guide for the Design and Construction of Mill Buildings
(AIST Tech Report No. 13, 2020)

**Industrial Building Design 3rd ed. (AISC Steel Design
Guide Number 7, 2019)**



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REFERENCES

- Fisher, J.W., Frank, K.H., Hirt, M.A. and McNamee, B.M. (1970), “Effect of Weldments on the Fatigue Strength of Beams,” Report 102, National Cooperative Highway Research Program, Washington, DC.



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REFERENCES

- Fisher, J.W., Albrecht, P.A., Yen, B.T., Klingerman, D.J. and McNamee, B.M. (1974), “Fatigue Strength of Steel Beams with Welded Stiffeners and Attachments,” Report 147, National Cooperative Highway Research Program, Washington, DC.



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(Lehigh Preserve)



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FATIGUE: SUMMARY

The two significant variables that impact service life are:

- Stress Range
- Detail Type (stress category)

Improving fatigue life involves:

- Decreasing the severity of the stress concentrations.
- Decreasing the stress range.



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FATIGUE: SUMMARY

AISC Appendix 3

- Calculate the applied stress range at each critical condition in the cyclically loaded structure and confirm it does not exceed the allowable stress range.
- Carefully develop details to avoid inadvertent restraint and unintended eccentricities.
- Specify the fabrication and erection work appropriately.



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Session 5 - Fatigue the End



Thank you!

AISC | Questions?



Individual Session Registrants

PDH Certificates

- You will receive an email on how to report attendance from: registration@aisc.org.
- Be on the lookout: Check your spam filter! Check your junk folder!
- Completely fill out online form. Don't forget to check the boxes next to each attendee's name!



Individual Session Registrants

PDH Certificates

- Reporting site (URL will be provided in the forthcoming email).
- Username: Same as AISC website username.
- Password: Same as AISC website password.



Individual Session Registrants

PDH Certificates

- Accommodations for Work-From-Home situations:
- AISC will provide the list of attendees from your company to report attendance. These are the only individuals that you should report for attending this session.
- The lists will be send out within 3 business days.



8-Session Registrants

PDH Certificates

One certificate will be issued at the conclusion of all 8 sessions.



8-Session Registrants

Access to the quiz

Information for accessing the quiz will be emailed to you by Thursday. It will contain a link to access the quiz. EMAIL COMES FROM NIGHTSCHOOL@AISC.ORG.

Quiz and attendance records

Posted Thursday mornings. www.aisc.org/nightschool -- Click on Current Course Details.

Reasons for quiz

- EEU – You must take all quizzes and the final exam to receive EEU.
- PDHs – If you watch a recorded session, you must pass quiz for PDHs.
- REINFORCEMENT – Reinforce what you learn tonight. Get more out of the course.

Note: If you attend the live presentation, you do not have to take the quizzes to receive PDHs



8-Session Registrants

Access to the recording

Information for accessing the recording will be emailed to you by Thursday. The recording will be available for four weeks. (For 8-session registrants only.) EMAIL COMES FROM NIGHTSCHOOL@AISC.ORG.

PDHs via recording

If you watch a recorded session, you must take *and pass* the quiz for PDHs.



8-Session Registrants

Night School Resources

Find all your handouts, quizzes and quiz scores, recording access, and attendance information all in one place!



8-Session Registrants

Night School Resources

Go to www.aisc.org and sign in.



Login

If you're an existing customer, please enter your username and password.

<p>USERNAME</p> <input type="text" value="Enter your username"/>	<p>DON'T HAVE AN ACCOUNT?</p> <p>My AISC allows you to access Engineering Journal articles and Design Guides you have downloaded from the bookstore.</p> <p>REGISTER NOW</p>
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<input type="checkbox"/> Remember Me	

8-Session Registrants

Night School Resources

Go to www.aisc.org and sign in.

<p>IN THIS SECTION</p> <ul style="list-style-type: none">Edit ProfileMy DownloadsMy Pending QuizzesMy EventsOrder HistoryCourse HistoryCourse Resources	<p>MyAISC</p> <hr/> <p>MY PROFILE</p> <p>Update your contact and address information.</p> <p>EDIT PROFILE</p> <hr/> <p>MY PURCHASED DOWNLOADS</p> <p>Access articles and documents that you have purchased.</p> <p>VIEW DOWNLOADS</p> <hr/> <p>MY COURSE RESOURCES</p> <p>View online resources for Night School and Live Webinar package registrations.</p> <p>VIEW RESOURCES</p>
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8-Session Registrants

Night School Resources



Course Resources

Event	Start Date
NS 13 8-Session Package-Night School 13 - Design of Industrial Buildings	1/30/2017 7:00:00 PM
NS 14 8-Session Package-Night School 14 - Fundamentals of Stability	6/5/2017 7:00:00 PM

8-Session Registrants

Night School Resources



Night School 13: Design of Industrial Buildings

8-SESSION PACKAGE RESOURCES

Event	Date	Handouts	Video	Quiz	Attendance
NS13 - Design Criteria	1/30/2017 7:00:00 PM	Handouts	View Passcode: NS13DSN	Pass Score: 80	Pending
NS13 - Economic Considerations	2/6/2017 7:00:00 PM	Handouts	Available 02/08/2017 5pm EST	Available 02/08/2017 5pm EST	Pending
NS13 - Lateral Load Systems and Details	2/13/2017 7:00:00 PM	Handouts	Available 02/15/2017 5pm EST	Available 02/15/2017 5pm EST	Pending
NS13 - Preliminary Design Procedures	2/27/2017 7:00:00 PM	Handouts	Available 03/01/2017 5pm EST	Available 03/01/2017 5pm EST	Pending
NS13 - Crane Girder Design and Frame Analysis	3/6/2017 7:00:00 PM	Handouts	Available 03/08/2017 5pm EST	Available 03/08/2017 5pm EST	Pending
NS13 - Frame Member and Connection Design	3/13/2017 7:00:00 PM	Handouts	Available 03/15/2017 5pm EST	Available 03/15/2017 5pm EST	Pending
NS13 - Transfer Crane Girder & Longitudinal Bldg Bracing Dsn	3/27/2017 7:00:00 PM	Handouts	Available 03/29/2017 5pm EST	Available 03/29/2017 5pm EST	Pending
NS13 - Building Envelope and Bracing Design	4/3/2017 7:00:00 PM	Handouts	Available 04/05/2017 5pm EST	Available 04/05/2017 5pm EST	Pending

8-Session Registrants

Night School Resources

- Weekly “quiz and recording” email.
- Weekly updates of the master quiz and attendance record, found at www.aisc.org/nightschool23. Scroll down to Quiz and Attendance records.
 - Updated on Thursday mornings.

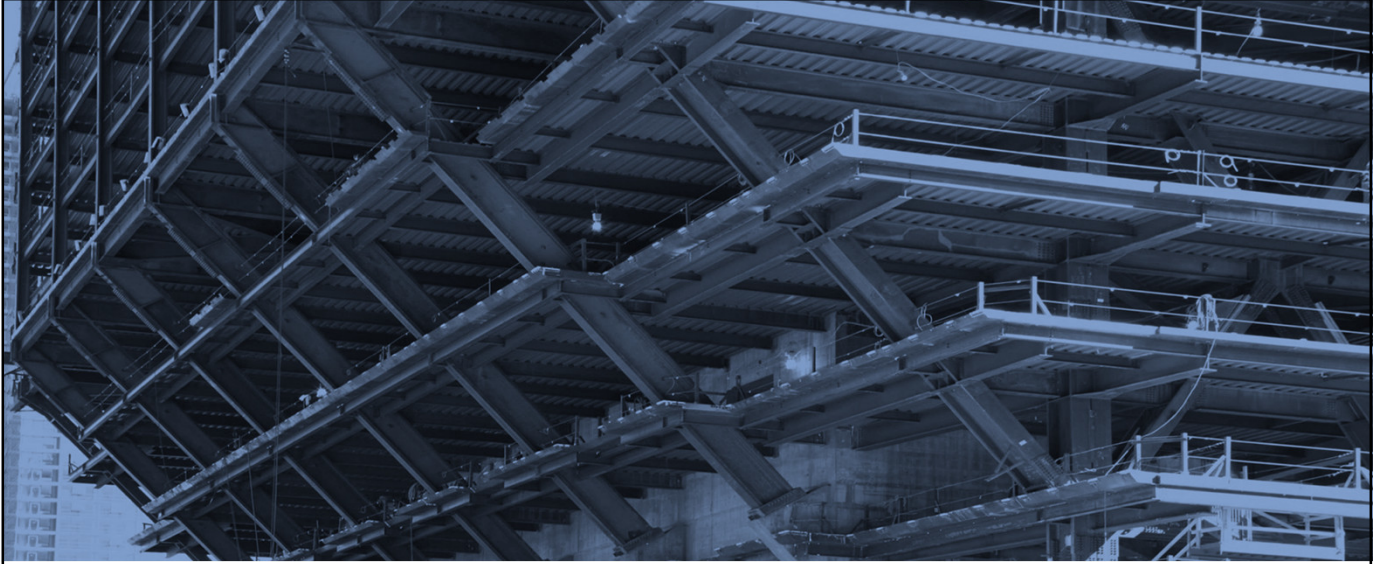


8-Session Registrants

Night School Resources

- Webinar connection information
 - Reminder email sent out Tuesday mornings
- Links to handouts also found here





AISC | Thank you



Smarter.
Stronger.
Steel.