APPENDIX 3

FATIGUE

This appendix applies to 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.

> **User Note:** See AISC *Seismic Provisions for Structural Steel Buildings* for structures subject to seismic loads.

The appendix is organized as follows:

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_{TH}, 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 $0.66F_y$. 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).

3.2. CALCULATION OF MAXIMUM STRESSES AND STRESS RANGES

Calculated stresses shall be based upon elastic analysis. Stresses shall not be amplified by stress concentration factors for geometrical discontinuities.

For bolts and threaded rods subject to axial tension, the calculated stresses shall include the effects of prying action, if any. In the case of axial stress combined with bending, the maximum stresses of each kind shall be those determined for concurrent arrangements of the applied load.

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.

For axially loaded angle members where the center of gravity of the connecting welds lies between the line of the center of gravity of the angle cross section and the center of the connected leg, the effects of eccentricity shall be ignored. If the center of gravity of the connecting welds lies outside this zone, the total stresses, including those due to joint eccentricity, shall be included in the calculation of stress range.

3.3. PLAIN MATERIAL AND WELDED JOINTS

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:

$$F_{SR} = 1{,}000\left(\frac{C_f}{n_{SR}}\right)^{0.333} \geq F_{TH} \tag{A-3-1}$$

$$F_{SR} = 6\,900\left(\frac{C_f}{n_{SR}}\right)^{0.333} \geq F_{TH} \tag{A-3-1M}$$

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

(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:

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

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

(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:

(1) Based upon crack initiation from the toe of the weld on the tension-loaded plate element (i.e., when $R_{PJP} = 1.0$), the allowable stress range, F_{SR}, shall be determined by Equation A-3-1 or A-3-1M for stress category C.

(2) Based upon crack initiation from the root of the weld, the allowable stress range, F_{SR}, on the tension loaded plate element using transverse PJP groove welds, with or without reinforcing or contouring fillet welds, the allowable stress range on the cross section at the root of the weld shall be determined by Equation A-3-3 or A-3-3M, for stress category C′ as follows:

$$F_{SR} = 1{,}000 R_{PJP} \left(\frac{4.4}{n_{SR}} \right)^{0.333} \tag{A-3-3}$$

$$F_{SR} = 6\,900 R_{PJP} \left(\frac{4.4}{n_{SR}} \right)^{0.333} \tag{A-3-3M}$$

where

R_{PJP}, the reduction factor for reinforced or nonreinforced transverse PJP groove welds, is determined as follows:

$$R_{PJP} = \frac{0.65 - 0.59\left(\frac{2a}{t_p} \right) + 0.72\left(\frac{w}{t_p} \right)}{t_p^{0.167}} \le 1.0 \tag{A-3-4}$$

$$R_{PJP} = \frac{1.12 - 1.01\left(\frac{2a}{t_p} \right) + 1.24\left(\frac{w}{t_p} \right)}{t_p^{0.167}} \le 1.0 \tag{A-3-4M}$$

$2a$ = length of the nonwelded root face in the direction of the thickness of the tension-loaded plate, in. (mm)
t_p = thickness of tension loaded plate, in. (mm)
w = leg size of the reinforcing or contouring fillet, if any, in the direction of the thickness of the tension-loaded plate, in. (mm)

If $R_{PJP} = 1.0$, the stress range will be limited by the weld toe and category C will control.

(3) Based upon crack initiation from the roots of a pair of transverse fillet welds on opposite sides of the tension loaded plate element, the allowable stress range, F_{SR}, on the cross section at the root of the welds shall be determined by Equation A-3-5 or A-3-5M, for stress category C″ as follows:

$$F_{SR} = 1{,}000R_{FIL}\left(\frac{4.4}{n_{SR}}\right)^{0.333} \tag{A-3-5}$$

$$F_{SR} = 6\,900R_{FIL}\left(\frac{4.4}{n_{SR}}\right)^{0.333} \tag{A-3-5M}$$

where

R_{FIL} = reduction factor for joints using a pair of transverse fillet welds only

$$= \frac{0.06 + 0.72\left(w / t_p\right)}{t_p^{0.167}} \le 1.0 \tag{A-3-6}$$

$$= \frac{0.103 + 1.24\left(w / t_p\right)}{t_p^{0.167}} \le 1.0 \tag{A-3-6M}$$

If R_{FIL} = 1.0, the stress range will be limited by the weld toe and category C will control.

User Note: Stress categories C′ and C″ are cases where the fatigue crack initiates in the root of the weld. These cases do not have a fatigue threshold and cannot be designed for an infinite life. Infinite life can be approximated by use of a very high cycle life such as 2×10^8. Alternatively, if the size of the weld is increased such that R_{FIL} or R_{PJP} is equal to 1.0, then the base metal controls, resulting in stress category C, where there is a fatigue threshold and the crack initiates at the toe of the weld.

3.4. BOLTS AND THREADED PARTS

In bolts and threaded parts, the range of stress of the applied cyclic load shall not exceed the allowable stress range computed as follows.

(a) For mechanically fastened connections loaded in shear, the maximum range of stress in the connected material of the applied cyclic load shall not exceed the allowable stress range computed using Equation A-3-1 or A-3-1M, where C_f and F_{TH} are taken from Section 2 of Table A-3.1.

(b) For high-strength bolts, common bolts, threaded anchor rods, and hanger rods with cut, ground or rolled threads, the maximum range of tensile stress on the net tensile area from applied axial load and moment plus load due to prying action shall not exceed the allowable stress range computed using Equation A-3-1 or A-3-1M, where C_f and F_{TH} are taken from Case 8.5 (stress category G). The net area in tension, A_t, is given by Equation A-3-7 or A-3-7M.

$$A_t = \frac{\pi}{4}\left(d_b - \frac{0.9743}{n}\right)^2 \tag{A-3-7}$$

$$A_t = \frac{\pi}{4}\left(d_b - 0.9382p\right)^2 \tag{A-3-7M}$$

where

d_b = nominal diameter (body or shank diameter), in. (mm)
n = threads per in. (per mm)
p = pitch, in. per thread (mm per thread)

For joints in which the material within the grip is not limited to steel or joints that are not tensioned to the requirements of Table J3.1 or J3.1M, all axial load and moment applied to the joint plus effects of any prying action shall be assumed to be carried exclusively by the bolts or rods.

For joints in which the material within the grip is limited to steel and which are pretensioned to the requirements of Table J3.1 or J3.1M, an analysis of the relative stiffness of the connected parts and bolts is permitted to be used to determine the tensile stress range in the pretensioned bolts due to the total applied cyclic load and moment, plus effects of any prying action. Alternatively, the stress range in the bolts shall be assumed to be equal to the stress on the net tensile area due to 20% of the absolute value of the applied cyclic axial load and moment from dead, live and other loads.

3.5. FABRICATION AND ERECTION REQUIREMENTS FOR FATIGUE

Longitudinal steel backing, if used, shall be continuous. If splicing of steel backing is required for long joints, the splice shall be made with a complete-joint-penetration (CJP) groove weld, ground flush to permit a tight fit. If fillet welds are used to attach left-in-place longitudinal backing, they shall be continuous.

In transverse CJP groove welded T- and corner-joints, a reinforcing fillet weld, not less than $^1/_4$ in. (6 mm) in size, shall be added at reentrant corners.

The surface roughness of thermally cut edges subject to cyclic stress ranges, that include tension, shall not exceed 1,000 μin. (25 μm), where *Surface Texture, Surface Roughness, Waviness, and Lay* (ASME B46.1) is the reference standard.

User Note: AWS C4.1 Sample 3 may be used to evaluate compliance with this requirement.

Reentrant corners at cuts, copes and weld 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.

For transverse butt joints in regions of tensile stress, weld tabs shall be used to provide for cascading the weld termination outside the finished joint. 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.

Fillet welds subject to cyclic loading normal to the outstanding legs of 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; the end return distance shall not exceed four times the weld size.

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 or A-3-1M applies only to welds that have been ultrasonically or radiographically tested and meet the acceptance requirements of *Structural Welding Code—Steel* (AWS D1.1/D1.1M) clause 6.12.2 or clause 6.13.2.

TABLE A-3.1
Fatigue Design Parameters

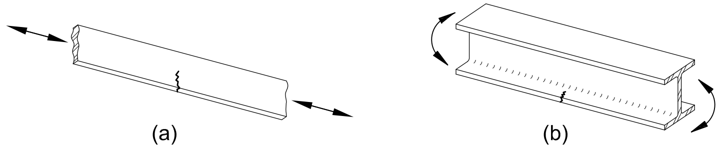
Description	Stress Category	Constant C_f	Threshold F_{TH}, ksi (MPa)	Potential Crack Initiation Point
SECTION 1—PLAIN MATERIAL AWAY FROM ANY WELDING				
1.1 Base metal, except noncoated weathering steel, with as-rolled or cleaned surfaces; flame-cut edges with surface roughness value of 1,000 µin. (25 µm) or less, but without reentrant corners	A	25	24 (165)	Away from all welds or structural connections
1.2 Noncoated weathering steel base metal with as-rolled or cleaned surfaces; flame-cut edges with surface roughness value of 1,000 µin. (25 µm) 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				At any external edge or at hole perimeter
$R \geq 1$ 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)	
$R \geq 3/8$ in. (10 mm) and the radius, R, need not be ground to a bright metal surface	E′	0.39	2.6 (18)	
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)	
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)	

TABLE A-3.1 (continued)
Fatigue Design Parameters

Illustrative Typical Examples

SECTION 1—PLAIN MATERIAL AWAY FROM ANY WELDING

1.1 and 1.2



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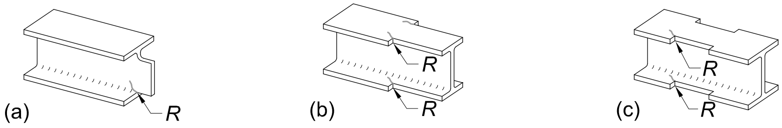

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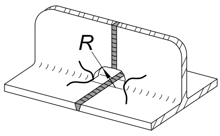

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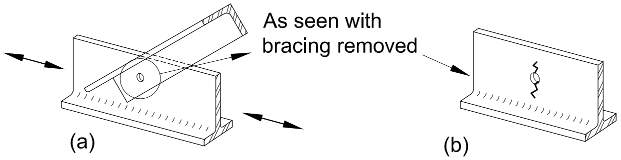


TABLE A-3.1 (continued)
Fatigue Design Parameters

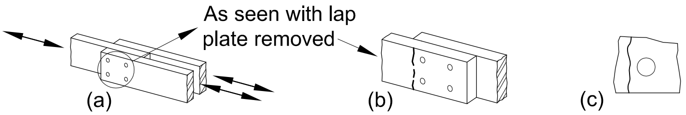
Description	Stress Category	Constant C_f	Threshold F_{TH}, ksi (MPa)	Potential Crack Initiation Point
SECTION 2—CONNECTED MATERIAL IN MECHANICALLY FASTENED JOINTS				
2.1 Gross area of base metal in lap joints connected by high-strength bolts in joints satisfying all requirements for slip-critical connections	B	12	16 (110)	Through gross section near hole
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
2.3 Base metal at the net section of riveted joints	C	4.4	10 (69)	In net section originating at side of hole
2.4 Base metal at net section of eyebar head or pin plate	E	1.1	4.5 (31)	In net section originating at side of hole

TABLE A-3.1 (continued)
Fatigue Design Parameters

Illustrative Typical Examples

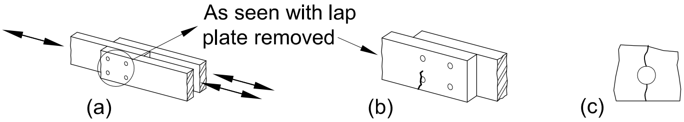
SECTION 2—CONNECTED MATERIAL IN MECHANICALLY FASTENED JOINTS

2.1



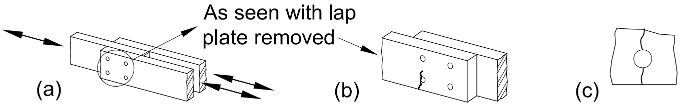
(Note: Figures are for slip-critical bolted connections.)

2.2



(Note: Figures are for bolted connections designed to bear, meeting the requirements of slip-critical connections.)

2.3



(Note: Figures are for snug-tightened bolts, rivets, or other mechanical fasteners.)

2.4

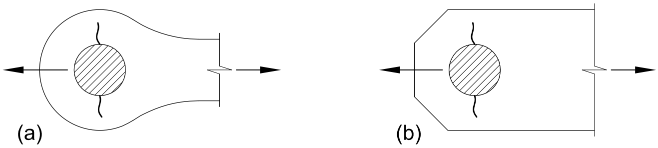


TABLE A-3.1 (continued)
Fatigue Design Parameters

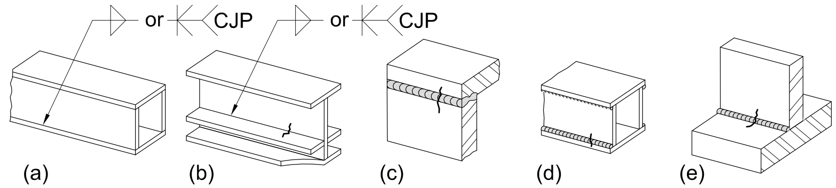
Description	Stress Category	Constant C_f	Threshold F_{TH}, ksi (MPa)	Potential Crack Initiation Point
SECTION 3—WELDED JOINTS JOINING COMPONENTS OF BUILT-UP MEMBERS				
3.1 Base metal and weld metal in members without attachments built up of plates or shapes connected by continuous longitudinal CJP groove welds, back gouged and welded from second side, or by continuous fillet welds	B	12	16 (110)	From surface or internal discontinuities in weld
3.2 Base metal and weld metal in members without attachments built up of plates or shapes, connected by continuous longitudinal CJP groove welds with left-in-place continuous steel backing, or by continuous PJP groove welds	B′	6.1	12 (83)	From surface or internal discontinuities in weld
3.3 Base metal at the ends of longitudinal welds that terminate at weld access holes in connected built-up members, as well as weld toes of fillet welds that wrap around ends of weld access holes				From the weld termination into the web or flange
Access hole $R \geq 1$ in. (25 mm) with radius, R, formed by predrilling, subpunching and reaming, or thermally cut and ground to bright metal surface	D	2.2	7 (48)	
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)	
3.4 Base metal at ends of longitudinal intermittent fillet weld segments	E	1.1	4.5 (31)	In connected material at start and stop locations of any weld
3.5 Base metal at ends of partial length welded coverplates narrower than the flange having square or tapered ends, with or without welds across the ends				In flange at toe of end weld (if present) or in flange at termination of longitudinal weld
$t_f \leq 0.8$ in. (20 mm)	E	1.1	4.5 (31)	
$t_f > 0.8$ in. (20 mm) where t_f = thickness of member flange, in. (mm)	E′	0.39	2.6 (18)	

TABLE A-3.1 (continued)
Fatigue Design Parameters

Illustrative Typical Examples

SECTION 3—WELDED JOINTS JOINING COMPONENTS OF BUILT-UP MEMBERS

3.1



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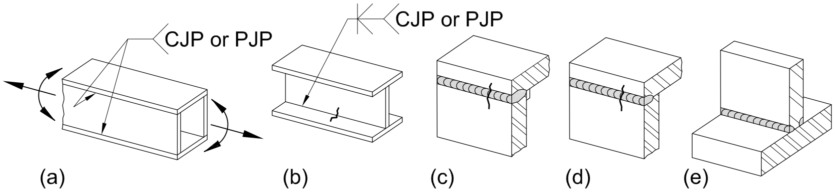

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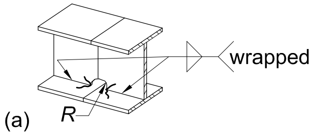

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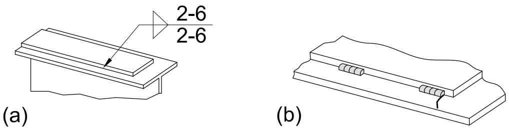

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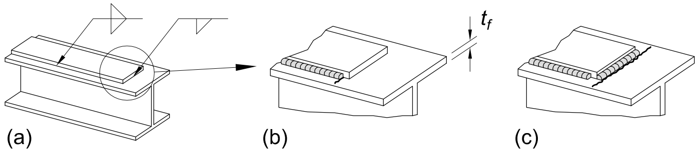
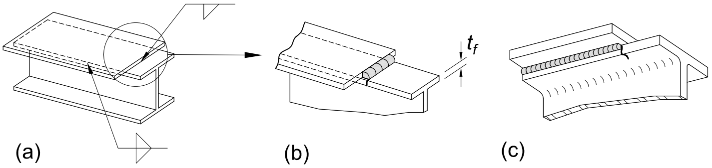
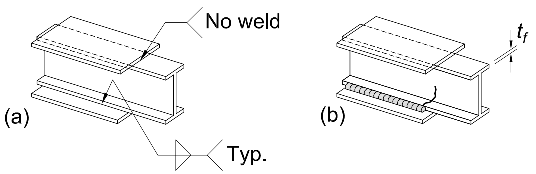


TABLE A-3.1 (continued)
Fatigue Design Parameters

Description	Stress Category	Constant C_f	Threshold F_{TH}, ksi (MPa)	Potential Crack Initiation Point
SECTION 3—WELDED JOINTS JOINING COMPONENTS OF BUILT-UP MEMBERS (cont'd)				
3.6 Base metal at ends of partial length welded coverplates or other attachments wider than the flange with welds across the ends				In flange at toe of end weld or in flange at termination of longitudinal weld or in edge of flange
$t_f \le 0.8$ in. (20 mm)	E	1.1	4.5 (31)	
$t_f > 0.8$ in. (20 mm)	E′	0.39	2.6 (18)	
3.7 Base metal at ends of partial length welded coverplates wider than the flange without welds across the ends				In edge of flange at end of coverplate weld
$t_f \le 0.8$ in. (20 mm)	E′	0.39	2.6 (18)	
$t_f > 0.8$ in. (20 mm) is not permitted	None	–	–	
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				Initiating from end of any weld termination extending into the base metal
$t_f \le 0.5$ in. (13 mm)	E	1.1	4.5 (31)	
$t_f > 0.5$ in. (13 mm)	E′	0.39	2.6 (18)	
where t = connected member thickness, as shown in Case 4.1 figure, in. (mm)				

TABLE A-3.1 (continued)
Fatigue Design Parameters

Illustrative Typical Examples
SECTION 3—WELDED JOINTS JOINING COMPONENTS OF BUILT-UP MEMBERS (cont'd)
3.6 
3.7 
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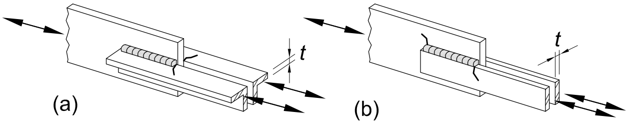
4.1 

TABLE A-3.1 (continued)
Fatigue Design Parameters

Description	Stress Category	Constant C_f	Threshold F_{TH}, ksi (MPa)	Potential Crack Initiation Point
SECTION 5—WELDED JOINTS TRANSVERSE TO DIRECTION OF STRESS				
5.1 Weld metal and base metal in or adjacent to CJP groove welded splices in plate, rolled shapes, or built-up cross sections with no change in cross section with welds ground essentially parallel to the direction of stress and inspected in accordance with Section 3.6	B	12	16 (110)	From internal discontinuities in weld metal or along the fusion boundary
5.2 Weld metal and base metal in or adjacent to CJP groove welded splices with welds ground essentially parallel to the direction of stress at transitions in thickness or width made on a slope no greater than 1:2$^1/_2$ and inspected in accordance with Section 3.6				From internal discontinuities in metal or along the fusion boundary or at start of transition when $F_y \geq 90$ ksi (620 MPa)
$F_y < 90$ ksi (620 MPa)	B	12	16 (110)	
$F_y \geq 90$ ksi (620 MPa)	B′	6.1	12 (83)	
5.3 Base metal and weld metal in or adjacent to CJP groove welded splices with welds ground essentially parallel to the direction of stress at transitions in width made on a radius, *R*, of not less than 24 in. (600 mm) with the point of tangency at the end of the groove weld and inspected in accordance with Section 3.6.	B	12	16 (110)	From internal discontinuities in weld metal or along the fusion boundary
5.4 Weld metal and base metal in or adjacent to CJP groove welds in T- or corner-joints or splices, without transitions in thickness or with transition in thickness having slopes no greater than 1:2$^1/_2$, when weld reinforcement is not removed, and is inspected in accordance with Section 3.6	C	4.4	10 (69)	From weld extending into base metal or into weld metal

TABLE A-3.1 (continued)
Fatigue Design Parameters

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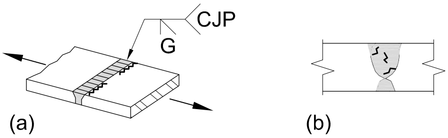
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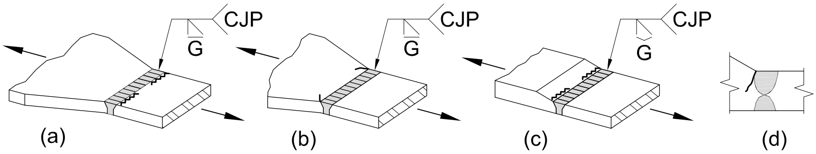
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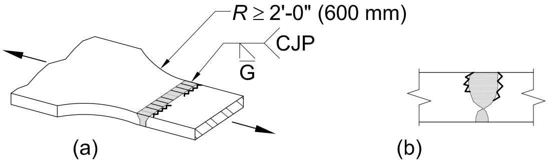
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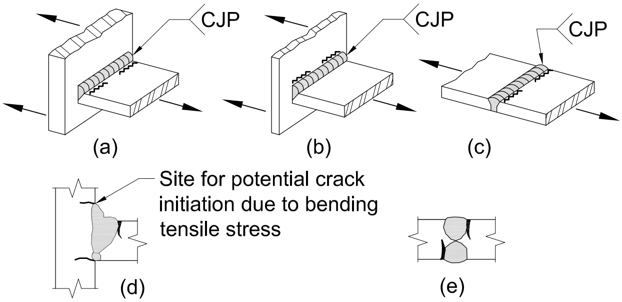
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TABLE A-3.1 (continued)
Fatigue Design Parameters

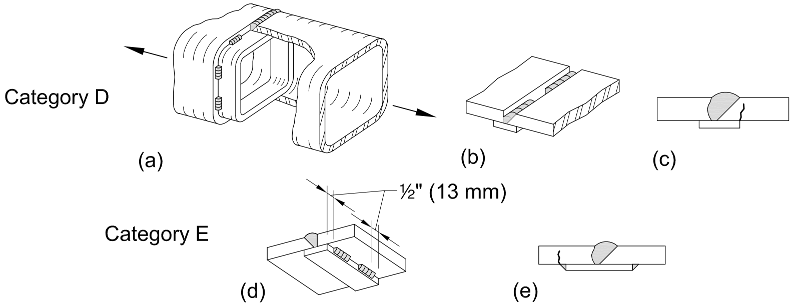
Description	Stress Category	Constant C_f	Threshold F_{TH}, ksi (MPa)	Potential Crack Initiation Point
SECTION 5—WELDED JOINTS TRANSVERSE TO DIRECTION OF STRESS				
5.5 Base metal and weld metal in or adjacent to transverse CJP groove welded butt splices with backing left in place				From the toe of the groove weld or the toe of the weld attaching backing when applicable
Tack welds inside groove	D	2.2	7 (48)	
Tack welds outside the groove and not closer than $^1/_2$ in. (13 mm) to the edge of base metal	E	1.1	4.5 (31)	
5.6 Base metal and weld metal at transverse end connections of tension-loaded plate elements using PJP groove welds in butt, T- or corner-joints, with reinforcing or contouring fillets; F_{SR} shall be the smaller of the toe crack or 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-3-3 or A-3-3M	None	Initiating at weld root extending into and through weld
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
5.8 Base metal of tension-loaded plate elements, and on built-up shapes and rolled beam webs or flanges at toe of transverse fillet welds adjacent to welded transverse stiffeners	C	4.4	10 (69)	From geometrical discontinuity at toe of fillet extending into base metal

TABLE A-3.1 (continued)
Fatigue Design Parameters

Illustrative Typical Examples

SECTION 5—WELDED JOINTS TRANSVERSE TO DIRECTION OF STRESS

5.5



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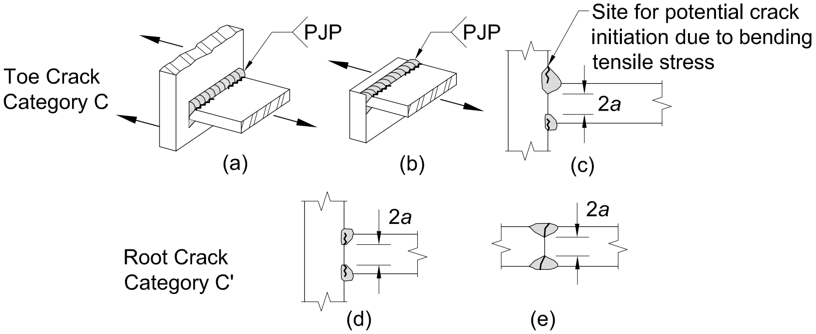

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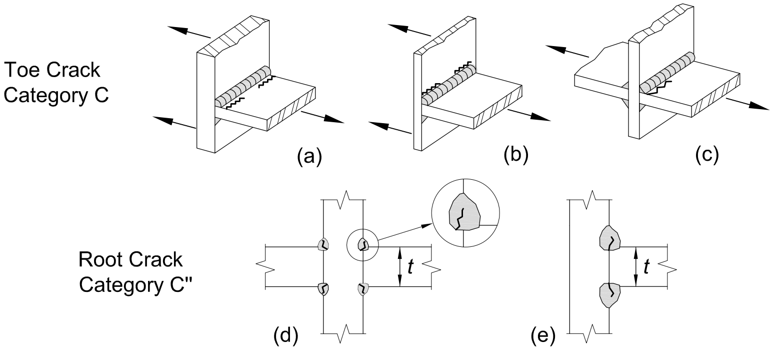


5.8

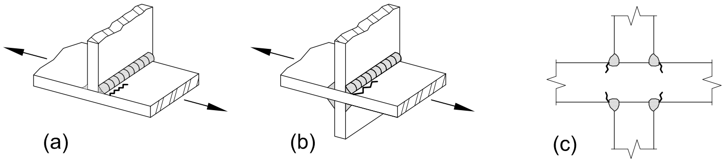


TABLE A-3.1 (continued)
Fatigue Design Parameters

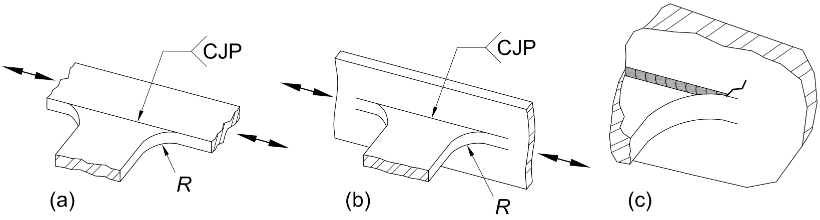
Description	Stress Category	Constant C_f	Threshold F_{TH}, ksi (MPa)	Potential Crack Initiation Point
SECTION 6—BASE METAL AT WELDED TRANSVERSE MEMBER CONNECTIONS				
6.1 Base metal of equal or unequal thickness at details attached by CJP groove welds subject to longitudinal loading only when the detail embodies a transition radius, R, with the weld termination ground smooth and inspected in accordance with Section 3.6				Near point of tangency of radius at edge of member
$R \geq 24$ in. (600 mm)	B	12	16 (110)	
6 in. $\leq R <$ 24 in. (150 mm $\leq R <$ 600 mm)	C	4.4	10 (69)	
2 in. $\leq R <$ 6 in. (50 mm $\leq R <$ 150 mm)	D	2.2	7 (48)	
$R <$ 2 in. (50 mm)	E	1.1	4.5 (31)	
6.2 Base metal at details of equal thickness attached by CJP groove welds, subject to transverse loading, with or without longitudinal loading, when the detail embodies a transition radius, R, with the weld termination ground smooth and inspected in accordance with Section 3.6				
(a) When weld reinforcement is removed				Near point of tangency of radius or in the weld or at fusion boundary or member or attachment
$R \geq 24$ in. (600 mm)	B	12	16 (110)	
6 in. $\leq R <$ 24 in. (150 mm $\leq R <$ 600 mm)	C	4.4	10 (69)	
2 in. $\leq R <$ 6 in. (50 mm $\leq R <$ 150 mm)	D	2.2	7 (48)	
$R <$ 2 in. (50 mm)	E	1.1	4.5 (31)	
(b) When weld reinforcement is not removed				At toe of the weld either along edge of member or the attachment
$R \geq 6$ in. (150 mm)	C	4.4	10 (69)	
2 in. $\leq R <$ 6 in. (50 mm $\leq R <$ 150 mm)	D	2.2	7 (48)	
$R <$ 2 in. (50 mm)	E	1.1	4.5 (31)	

TABLE A-3.1 (continued)
Fatigue Design Parameters

Illustrative Typical Examples

SECTION 6—BASE METAL AT WELDED TRANSVERSE MEMBER CONNECTIONS

6.1



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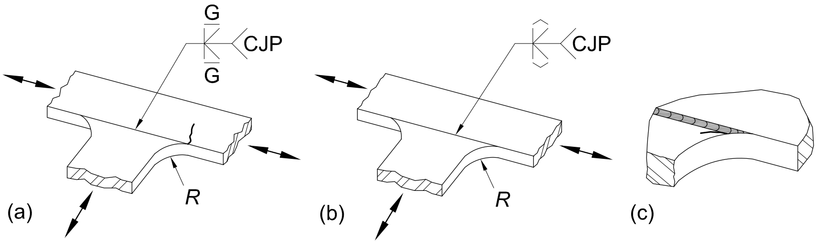


TABLE A-3.1 (continued)
Fatigue Design Parameters

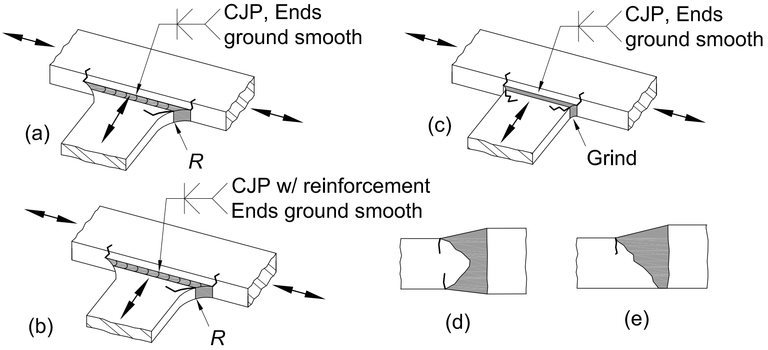
Description	**Stress Category**	**Constant C_f**	**Threshold F_{TH}, ksi (MPa)**	**Potential Crack Initiation Point**
SECTION 6—BASE METAL AT WELDED TRANSVERSE MEMBER CONNECTIONS (cont'd)				
6.3 Base metal at details of unequal thickness attached by CJP groove welds, subject to transverse loading, with or without longitudinal loading, when the detail embodies a transition radius, *R*, with the weld termination ground smooth and in accordance with Section 3.6				
(a) When weld reinforcement is removed				
$R > 2$ in. (50 mm)	D	2.2	7 (48)	At toe of weld along edge of thinner material
$R \leq 2$ in. (50 mm)	E	1.1	4.5 (31)	In weld termination in small radius
(b) When reinforcement is not removed				
Any radius	E	1.1	4.5 (31)	At toe of weld along edge of thinner material
6.4 Base metal of equal or unequal thickness, subject to longitudinal stress at transverse members, with or without transverse stress, attached by fillet or PJP groove welds parallel to direction of stress when the detail embodies a transition radius, *R*, with weld termination ground smooth				Initiating in base metal at the weld termination or at the toe of the weld extending into the base metal
$R > 2$ in. (50 mm)	D	2.2	7 (48)	
$R \leq 2$ in. (50 mm)	E	1.1	4.5 (31)	

TABLE A-3.1 (continued)
Fatigue Design Parameters

Illustrative Typical Examples

SECTION 6—BASE METAL AT WELDED TRANSVERSE MEMBER CONNECTIONS (cont'd)

6.3



6.4

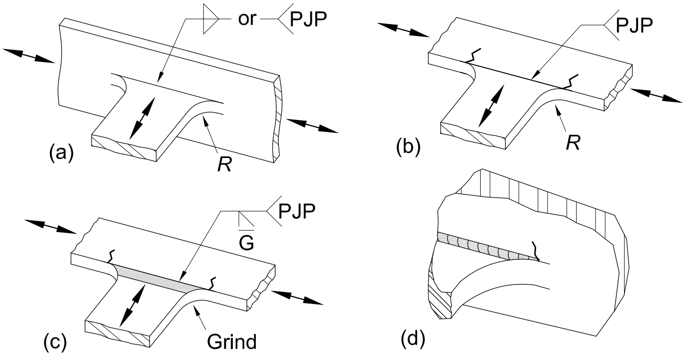


TABLE A-3.1 (continued)
Fatigue Design Parameters

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
$a < 2$ in. (50 mm) for any thickness, *b*	C	4.4	10 (69)	
2 in. (50 mm) $\le a \le$ lesser of 12*b* or 4 in. (100 mm)	D	2.2	7 (48)	
$a >$ lesser of 12*b* or 4 in. (100 mm) when $b \le 0.8$ in. (20 mm)	E	1.1	4.5 (31)	
$a > 4$ in. (100 mm) when $b > 0.8$ in. (20 mm)	E′	0.39	2.6 (18)	
7.2 Base metal subject to longitudinal stress at details attached by fillet or PJP groove welds, with or without transverse load on detail, when the detail embodies a transition radius, *R*, with weld termination ground smooth:				Initiating in base metal at the weld termination, extending into the base metal
$R > 2$ in. (50 mm)	D	2.2	7 (48)	
$R \le 2$ in. (50 mm)	E	1.1	4.5 (31)	

[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.

TABLE A-3.1 (continued)
Fatigue Design Parameters

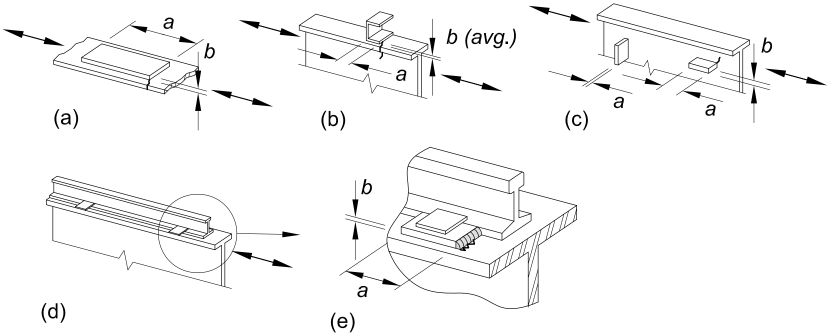
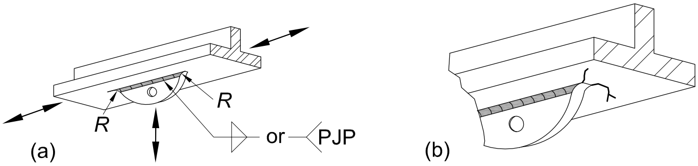
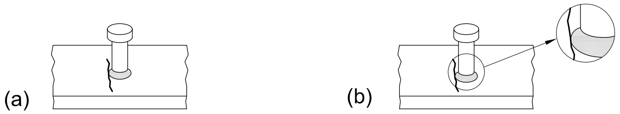
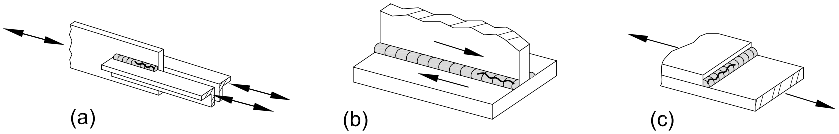
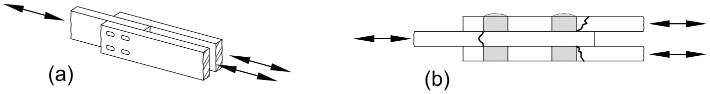
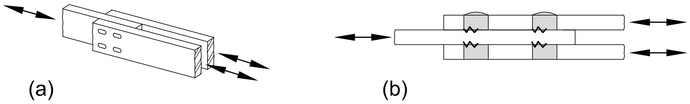
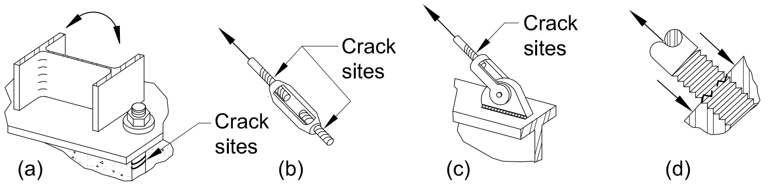
Illustrative Typical Examples
SECTION 7—BASE METAL AT SHORT ATTACHMENTS[a]
7.1 
7.2 

TABLE A-3.1 (continued)
Fatigue Design Parameters

Description	Stress Category	Constant C_f	Threshold F_{TH}, ksi (MPa)	Potential Crack Initiation Point
SECTION 8—MISCELLANEOUS				
8.1 Base metal at steel headed stud anchors attached by fillet weld or automatic stud welding	C	4.4	10 (69)	At toe of weld in base metal
8.2 Shear on throat of any fillet weld, continuous or intermittent, longitudinal or transverse	F	See Eq. A-3-2 or A-3-2M	See Eq. A-3-2 or A-3-2M	Initiating at the root of the fillet weld, extending into the weld
8.3 Base metal at plug or slot welds	E	1.1	4.5 (31)	Initiating in the base metal at the end of the plug or slot weld, extending into the base metal
8.4 Shear on plug or slot welds	F	See Eq. A-3-2 or A-3-2M	See Eq. A-3-2 or A-3-2M	Initiating in the weld at the faying surface, extending into the weld
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

TABLE A-3.1 (continued)
Fatigue Design Parameters

	Illustrative Typical Examples
SECTION 8—MISCELLANEOUS	
8.1	
8.2	
8.3	
8.4	
8.5	

Appendix 3 Commentary

APPENDIX 3

FATIGUE

When the limit state 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 concentrations associated with particular details. Issues of fatigue are not normally encountered in building design; however, when encountered and if the severity is great enough, fatigue is of concern and all provisions of this Appendix must be satisfied.

3.1. GENERAL PROVISIONS

This Appendix deals with high cycle fatigue (i.e., > 20,000 cycles); this behavior occurs when elastic stresses are involved. In situations where inelastic (plastic) stresses are involved, fatigue cracks may initiate at far fewer than 20,000 cycles—perhaps as few as a dozen. However, unlike the conditions prescribed in this Appendix, low cycle fatigue involves cyclic, inelastic stresses. This is because the applicable cyclic allowable stress range will be limited by the static allowable stress. At low levels of cyclic tensile stress, a point is reached where the stress range is so low that fatigue cracking will not initiate regardless of the number of cycles of loading. This level of stress is defined as the fatigue threshold, F_{TH}.

Extensive test programs using full-size specimens, substantiated by theoretical stress analysis, have confirmed the following general conclusions (Fisher et al., 1970; Fisher et al., 1974):

(1) Stress range and notch 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 steels with a specified minimum yield stress of 36 to 100 ksi (250 to 690 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 therefore, at higher temperatures, crack growth rates increase. At 500°F (260°C), crack growth rates on ASTM A212B steel (ASTM, 1967) are essentially the same as for room temperature (Hertzberg et al., 2012). The Appendix is conservatively limited to applications involving temperatures not to exceed 300°F (150°C). Elevated temperature applications may also have corrosion effects that are not considered by the Appendix.

The Appendix does not have a lower temperature limit because fatigue crack growth rates are lower. Fatigue tests as low as −100°F (−75°C) have been conducted with no observed change in crack growth rates (Roberts et al., 1980). It should be recognized that at low temperatures, brittle fracture concerns increase. The critical size to which a crack can grow before the onset of brittle fracture will be smaller for low temperature applications than will be the case for a room temperature application.

3.2. CALCULATION OF MAXIMUM STRESSES AND STRESS RANGES

Fluctuation in stress that does not involve tensile stress does not cause crack propagation and is not considered to be a fatigue situation. On the other hand, in elements of members subject solely to calculated compressive stress, fatigue cracks may initiate in regions of high tensile residual stress. In such situations, the cracks generally do not propagate beyond the region of the residual tensile stress, because the residual stress is relieved by the crack. For this reason, stress ranges that are completely in compression need not be investigated for fatigue. For cases involving cyclic reversal of stress, the calculated stress range must be taken as the sum of the compressive stress and the tensile stress caused by different directions or patterns of the applied live load. When part of the stress cycle is compressive, the stress range may exceed $0.66F_y$.

3.3. PLAIN MATERIAL AND WELDED JOINTS

Fatigue resistance has been derived from an exponential relationship between the number of cycles to failure, N, and the stress range, S_r, called an S-N relationship, of the form

$$N = \frac{C_f}{S_r^n} \tag{C-A-3-1}$$

The general relationship is often plotted as a linear log-log function (Log $N = A - n$ Log S_r). Figure C-A-3.1 shows the family of fatigue resistance curves identified as stress categories A, B, B′, C, D, E, E′ and G. These relationships were established based on an extensive database developed in the United States and abroad (Keating and Fisher, 1986). The allowable stress range has been developed by adjusting the coefficient, C_f, so that a design curve is provided that lies two standard deviations of the standard error of estimate of the fatigue cycle life below the mean S-N relationship of the actual test data. These values of C_f correspond to a probability of failure of 2.5% of the design life.

The number of stress range fluctuations in a design life, n_{SR}, in Equation A-3-1, can often be calculated as

$$\begin{aligned} n_{SR} = {} & \text{(number of stress fluctuations per day)} \times \\ & \text{(365 days)} \times \text{(years in design life)} \end{aligned} \tag{C-A-3-2}$$

Stress category F is shown in Figure C-A-3.2 and has a slope different than the other stress categories. The fatigue resistance of stress category C′ or C″ details is determined by applying a reduction factor, R_{PJP} or R_{FIL}, respectively, to the stress category C stress range, which shifts the fatigue resistance curve for stress category C downward by a factor proportional to the reduction. Unlike stress category C, stress category C′ and C″ details do not have a fatigue threshold.

Prior to the 1999 AISC *Load and Resistance Factor Design Specification for Structural Steel Buildings* (AISC, 2000b), stepwise tables meeting the criteria discussed in the foregoing, including cycles of loading, stress categories, and allowable stress ranges were provided in the Specification. A single table format (Table A-3.1) was introduced in the 1999 AISC LRFD *Specification* that provides the stress categories, ingredients for the applicable equation, and information and examples, including the sites of concern for potential crack initiation (AISC, 2000b).

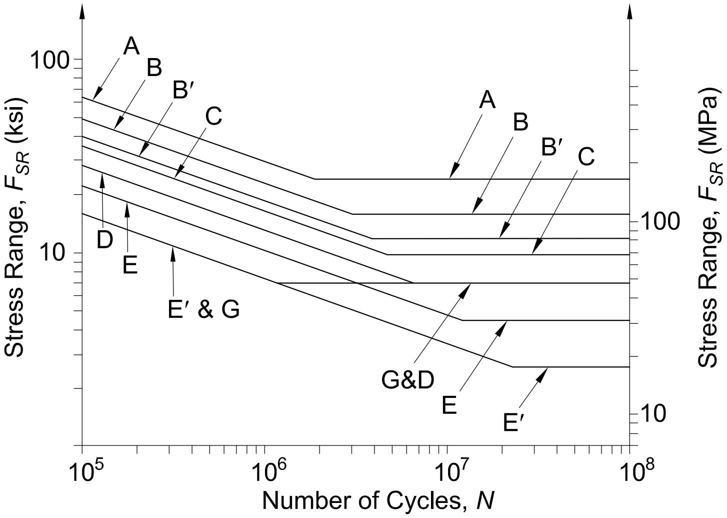


Fig. C-A-3.1. Fatigue resistance curves.

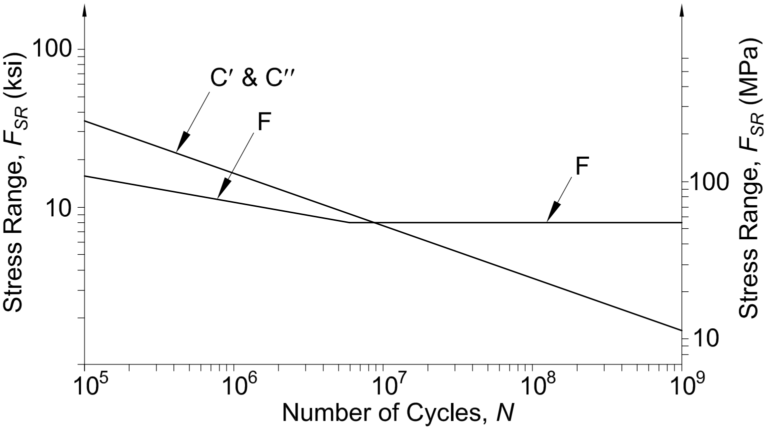


Fig. C-A-3.2. Fatigue resistance curves for stress categories C and F.

Table A-3.1 is organized into eight sections of general conditions for fatigue design, as follows:

(1) Section 1 provides information and examples for the steel material at copes, holes, cutouts or as produced.

(2) Section 2 provides information and examples for various types of mechanically fastened joints, including eyebars and pin plates.

(3) Section 3 provides information related to welded connections used to join built-up members, such as longitudinal welds, access holes and reinforcements.

(4) Section 4 deals only with longitudinal load carrying fillet welds at shear splices.

(5) Section 5 provides information for various types of groove and fillet welded joints that are transverse to the applied cyclic stress.

(6) Section 6 provides information on a variety of groove-welded attachments to flange tips and web plates, as well as similar attachments, connected with either fillet or partial-joint-penetration groove welds.

(7) Section 7 provides information on several short attachments to structural members.

(8) Section 8 collects several miscellaneous details, such as shear connectors, shear on the throat of fillet, plug and slot welds, and their impact on base metal. It also provides for tension on the stress area of various bolts, threaded anchor rods, and hangers.

A similar format and consistent criteria are used by other specifications.

When fabrication details involving more than one stress category occur at the same location in a member, the stress range at that location must be limited to that of the most restrictive category. The need for a member larger than required by static loading will often be eliminated by locating notch-producing fabrication details in regions subject to smaller ranges of stress.

A detail not explicitly covered before 1989 (AISC, 1989) was added in the 1999 AISC LRFD *Specification* (AISC, 2000b) to cover tension-loaded plate elements connected at their end by transverse partial-joint-penetration groove or fillet welds in which there is more than a single site for the initiation of fatigue cracking, one of which will be more critical than the others depending upon welded joint type and size, and material thickness (Frank and Fisher, 1979). Regardless of the site within the joint at which potential crack initiation is considered, the allowable stress range provided is applicable to connected material at the toe of the weld.

3.4. BOLTS AND THREADED PARTS

The fatigue resistance of bolts subject to tension is predictable in the absence of pretension and prying action; provisions are given for such nonpretensioned details as hanger rods and anchor rods. In the case of pretensioned bolts, deformation of the connected parts through which pretension is applied introduces prying action, the magnitude of which is not completely predictable (Kulak et al., 1987). The effect of prying is not limited to a change in the average axial tension on the bolt but includes bending in the threaded area under the nut. Because of the uncertainties in calculating prying effects, definitive provisions for the allowable stress range for bolts subject to applied axial tension are not included in this Specification. To limit the uncertainties regarding prying action on the fatigue of pretensioned bolts in details which introduce prying, the allowable stress range provided in Table A-3.1 is appropriate for extended cyclic loading only if the prying induced by the applied load is small.

The tensile stress range of bolts that are pretensioned to the requirements of Table J3.1 or J3.1M can be conservatively approximated as 20% of the absolute value of the applied cyclic axial load and moment from dead, live and other loads. AISC Design Guide 17, *High Strength Bolts: A Primer for Structural Engineers* (Kulak, 2002) states that the final bolt force is the initial pretension force plus a component of the externally applied load that depends on the relative areas of the bolt and the area of the connected material in compression. Test results show that this approach is a good predictor and that the increase in bolt pretension can be expected to be on the order of not more than about 5% to 10%, which affirms that the 20% rule is a conservative upper bound. The approximated stress range is compared with the allowable and threshold stress range.

Fatigue provisions in Appendix 3 and in the RCSC *Specification* (RCSC, 2014) are applied differently, but produce similar results. Some key differences are:

(1) Appendix 3 allows bolts that are pretensioned or not pretensioned to be subjected to cyclic axial loads, where the RCSC *Specification* only allows pretensioned bolts.

(2) Appendix 3 is applied using a bolt net area in tension, where RCSC *Specification* Table 5.2 is applied based upon the cross-sectional area determined from the nominal diameter.

(3) Appendix 3 is applied by determining a maximum allowable stress range and a stress range threshold regardless of the bolt material, where RCSC *Specification* Table 5.2 is applied by determining a maximum bolt stress, which does depend on the bolt material. Therefore, the stresses obtained from Appendix 3 should be compared to the tensile stress range including prying, while the stresses obtained from RCSC *Specification* Table 5.2 should be compared to the total applied tensile stress including prying.

Nonpretensioned fasteners are not permitted under this Specification for joints subject to cyclic shear forces. Bolts installed in joints meeting all the requirements for slip-critical connections survive unharmed when subject to cyclic shear stresses sufficient to fracture the connected parts; provisions for such bolts are given in Section 2 of Table A-3.1.

3.5. FABRICATION AND ERECTION REQUIREMENTS FOR FATIGUE

It is essential that when longitudinal backing bars are to be left in place, they be continuous or spliced using flush-ground complete-joint-penetration groove welds before attachment to the parts being joined. Otherwise, the transverse nonfused section constitutes a crack-like defect that can lead to premature fatigue failure or even brittle fracture of the built-up member.

Welds that attach left-in-place longitudinal backing to the structural member will affect the fatigue performance of the structural member. Continuous longitudinal fillet welds are stress category B; intermittent fillet welds are stress category E. Longitudinal backing may be attached to the joint by tack welding in the groove, attaching the backing to one member with a fillet weld, or attaching the backing to both members with fillet welds.

In transversely loaded joints subjected to tension, a lack-of-fusion plane in T-joints acts as an initial crack-like condition. In groove welds, the root at the backing bar often has discontinuities that can reduce the fatigue resistance of the connection. Removing the backing, back gouging the joint, and rewelding eliminates the undesirable discontinuities.

The addition of contoured fillet welds at transverse complete-joint-penetration groove welds in T- and corner joints and at reentrant corners reduces the stress concentration and improves fatigue resistance.

Experimental studies on welded built-up beams demonstrated that if the surface roughness of flame-cut edges was less than 1,000 μin. (25 μm), fatigue cracks would not develop from the flame-cut edge but from the longitudinal fillet welds connecting the beam flanges to the web (Fisher et al., 1970, 1974). This provides stress category B fatigue resistance without the necessity for grinding flame-cut edges.

Reentrant corners at cuts, copes and weld access holes provide a stress concentration point that can reduce fatigue resistance if discontinuities are introduced by punching or thermal cutting. Reaming sub-punched holes and grinding the thermally cut surface to bright metal prevents any significant reduction in fatigue resistance.

For Cases 1.4, 1.5 and 3.3 in Table A-3.1, Yam and Cheng (1990) reported that fatigue performance of reentrant corners less than 1 in. and not ground smooth is similar to stress category C when calculated with a stress concentration factor. To be consistent with other cases in this Appendix, reentrant corners with radii as small as $^3/_8$ in. and not ground are assigned stress category E′ and do not have to be calculated with a stress concentration factor. Reentrant corners with a radius of at least 1 in. and meeting surface requirements and NDE requirements are associated with stress category C, except for built-up members, where it is stress category D.

For Cases 3.5 and 3.6 in Table A-3.1, coverplates and other attachments wider than the flange with welds across the ends are subject to fatigue stress categories E and E′, depending on the thickness of the flange. There has been little research on connections with coverplates that are wider than the flange, where the flange is thicker than 0.8 in. and without welds across the ends; therefore, this detail is not recommended, as indicated for Case 3.7. Cover-plated flanges thicker than 0.8 in. are permitted when the ends are welded.

As shown in Case 7.1 in Table A-3.1, base metal subject to longitudinal loading at details with parallel or transverse welds with no transition radius is subject to stress category E or E′ fatigue stresses depending on the length and thickness of the attachment.

Attachments with no transition result in abrupt changes in stiffness of the stressed member corresponding to the stress the attachment attracts from the main member. Larger attachments attract more stress and make the attachment connection stiffer. These stiffness changes act as stress concentrations and aggravate fatigue crack growth.

The use of run-off tabs at transverse butt-joint groove welds enhances weld soundness at the ends of the joint. Subsequent removal of the tabs and grinding of the ends flush with the edge of the member removes discontinuities that are detrimental to fatigue resistance.