Life & Gradient Factors for ASME Class 1 Piping Component Analyses

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Summary

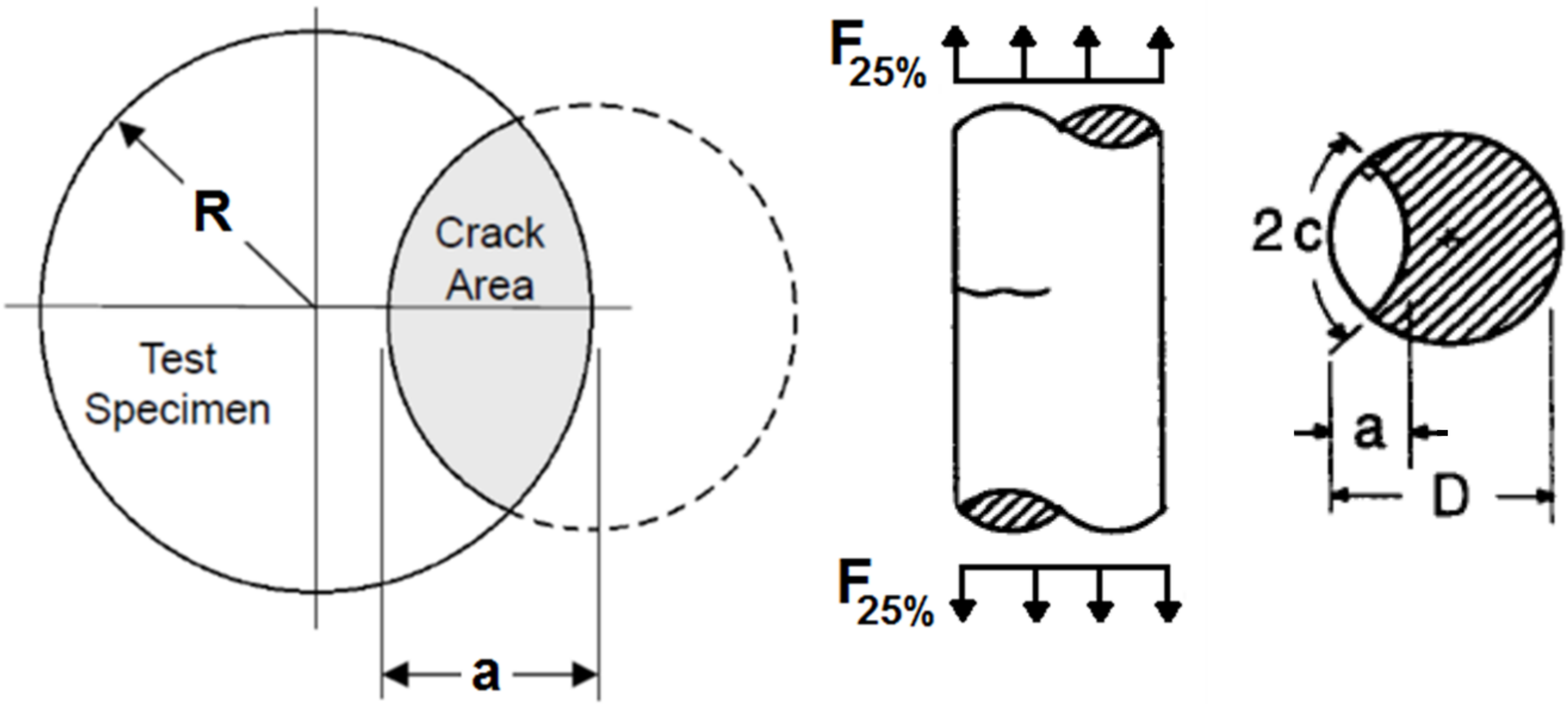
- Introduction
- Fatigue Life Test Data
- Life and Gradient Factors
- Stage I Life
- Stage II Life
- Life and Gradient Factor Regressions
- Example Problem
- Status

Introduction

- This work examined two aspects of ASME Code fatigue life (Usage) fatigue calculation procedures - e.g. NB-3222.4, NB-3650, or XIII 3222.4(e)(5)
  – allowable fatigue life is based on fatigue testing **small diameter** test specimens that are subsequently applied to all piping regardless of the actual thickness, and
  – all component cyclic stresses are treated as **uniform through-thicknes**s membrane stresses and do not consider the presence of actual through-thickness stress gradients.

FATIGUE LIFE TEST DATA

Test Specimen 25% Load Drop Crack Size



For constant displacement test: 25% load drop ($F_{25\%}$) occurs when crack area equals 25% of original test specimen area.

Fatigue Strain-Life Testing

- ASTM Standard E 606-04
  - Smooth push-pull specimens tested under fully reversed through-thickness uniform (membrane) displacement controlled loading
  - Determination of number of cycles to failure may vary. Current data based on force (load) drop of 25% or 50%.
- NUREG/CR-6909 Rev. 1
  - Argonne National Laboratory and Japanese data
  - Mixture of 25% and 50% load drop data (all data normalized to 25% load drop criteria)
  - Air test temperatures between 25°C and 290°C
  - Gauge diameters 0.2 in. (5-mm) to 0.375 in. (9.5-mm)

Observation: *25% load drop criteria was associated with an average 3-mm deep crack (Chopra and Shack 2001)*

LIFE & GRADIENT FACTORS

Life and Gradient Factors

$$U^{*}_{air} = U_{air} \times LF_{air} \times GF_{air}$$

LF accounts for increased Stage II life associated a with piping thicknesses greater than the 0.304 inch median gauge thickness associated with the NUREG/CR-6909 Rev. 1 **room temperature air** test data.

GF accounts for the increase in **room temperature air** Stage II life associated with through thickness stress gradients

$$U_{water} = U^{*}_{air} \times Fen$$

Stage I and Stage II life calculations for carbon steel (CS), low alloy steel (LAS) and stainless steel (SS) materials were based on material properties at room temperature (25°C).

Life Factor, LF

A life factor LF corrects fatigue usage estimates for increased Stage II life associated with component thicknesses greater than the **0.304 inch median gauge** thickness associated with the NUREG/CR-6909 **solid pin** test specimens.

$$LF = \frac{N_{3mm}}{N_{25\%}} = \frac{N_I + N_{II(3mm)}}{\left(N_I + N_{II(25\%)}\right)}$$

N_I = Stage 1 life in number of cycles between 10 μm (0.0004 inch) and 200 μm (0.008 inch) under uniform membrane cyclic strain

$N_{II(3mm)}$ = Stage II life in number of cycles between 200 μm (0.008 inch) and 3mm crack depth under uniform membrane cyclic strain

$N_{II(25\%)}$ = Stage II life in number of cycles between 200 μm (0.008 inch) and 25% load drop crack depth under uniform membrane cyclic strain

Gradient Factor, GF

GF accounts for the increase in Stage II life associated with through thickness stress gradients

$$GF = \frac{(N_I + N_{II})_{Membrane}}{(N_I)_{Membrane} + (N_{II})_{Gradient}}$$

where:

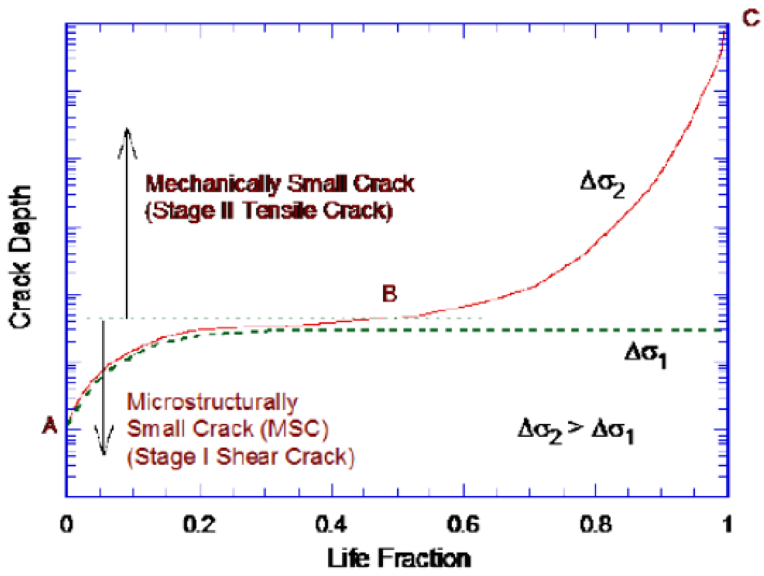
N_I = Stage 1 life between 10 μm (0.0004 inch) and 200 μm (0.008 inch)

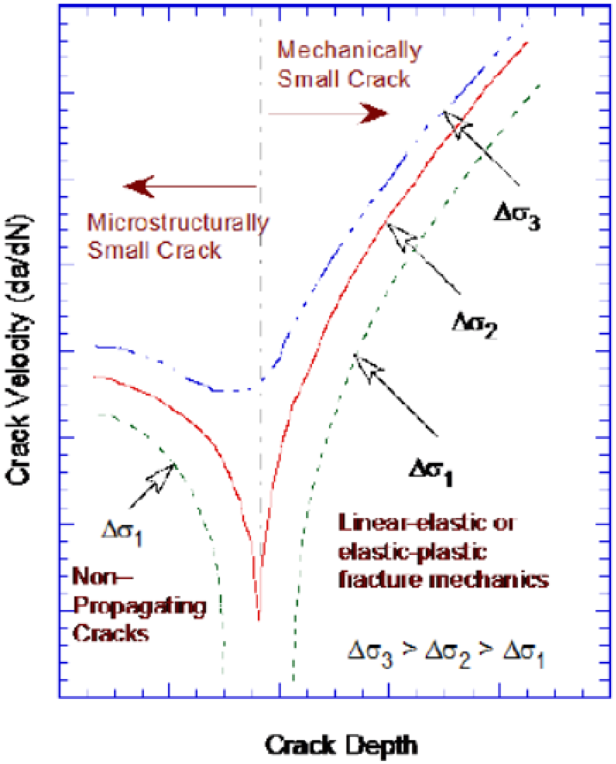
N_{II} = Stage II life between 200 μm (0.008 inch) and crack depth associated with a 25% load drop for the actual component thickness

STAGE I LIFE

Stage I and Stage II Life

- Two stages of fatigue crack growth
  - Stage I: Initiation and growth of “microstructurally small cracks”
  - Stage II: Growth of “mechanically small cracks”





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Stage I Life (i)

$$N_I = N_{Total} - N_{II}$$

$N_I =$ Stage 1 life in number of cycles between 10 μm and 200 μm (0.008 inch) under uniform membrane cyclic strain

$N_{Total} =$ the best estimate carbon steel total (Stage I and Stage II) cyclic life model in NUREG/CR-6909 Rev. 1 shown in Eq. 20

$N_{II} =$ represents the Stage II life required for a 0.008 in. mechanically small crack to grow to a depth of 0.118 in. (3 mm) under uniform membrane conditions

Assumption: *Stage I initiation and growth occurs under uniform membrane loading regardless of the absence or presence of linear and non-linear through-wall stress gradients.*

Test Specimen 25% load drop crack depths

Specimen Diameter, *2R* in. (cm)		Specimen Area in.^{2} (cm^2)		Crack Area in.^{2} (cm^2)		25% Load Drop Crack Depth, *a* in. (cm)	
0.304	**(0.772)**	**0.0725**	**(0.468)**	**0.0181**	**(0.117)**	**0.118**	**(0.300)**
0.344	(0.874)	0.0929	(0.599)	0.0232	(0.150)	0.133	(0.338)
0.438	(1.113)	0.1506	(0.972)	0.0377	(0.243)	0.170	(0.432)
0.719	(1.826)	0.4058	(2.618)	0.1015	(0.655)	0.279	(0.709)
1.125	(2.858)	0.9940	(6.413)	0.2490	(1.606)	0.436	(1.107)
1.325	(3.366)	1.3789	(8.896)	0.3447	(2.224)	0.513	(1.303)
1.968	(4.999)	3.0420	(19.626)	0.7600	(4.903)	0.762	(1.935)
2.344	(5.954)	4.3150	(27.839)	1.0790	(6.961)	0.908	(2.306)

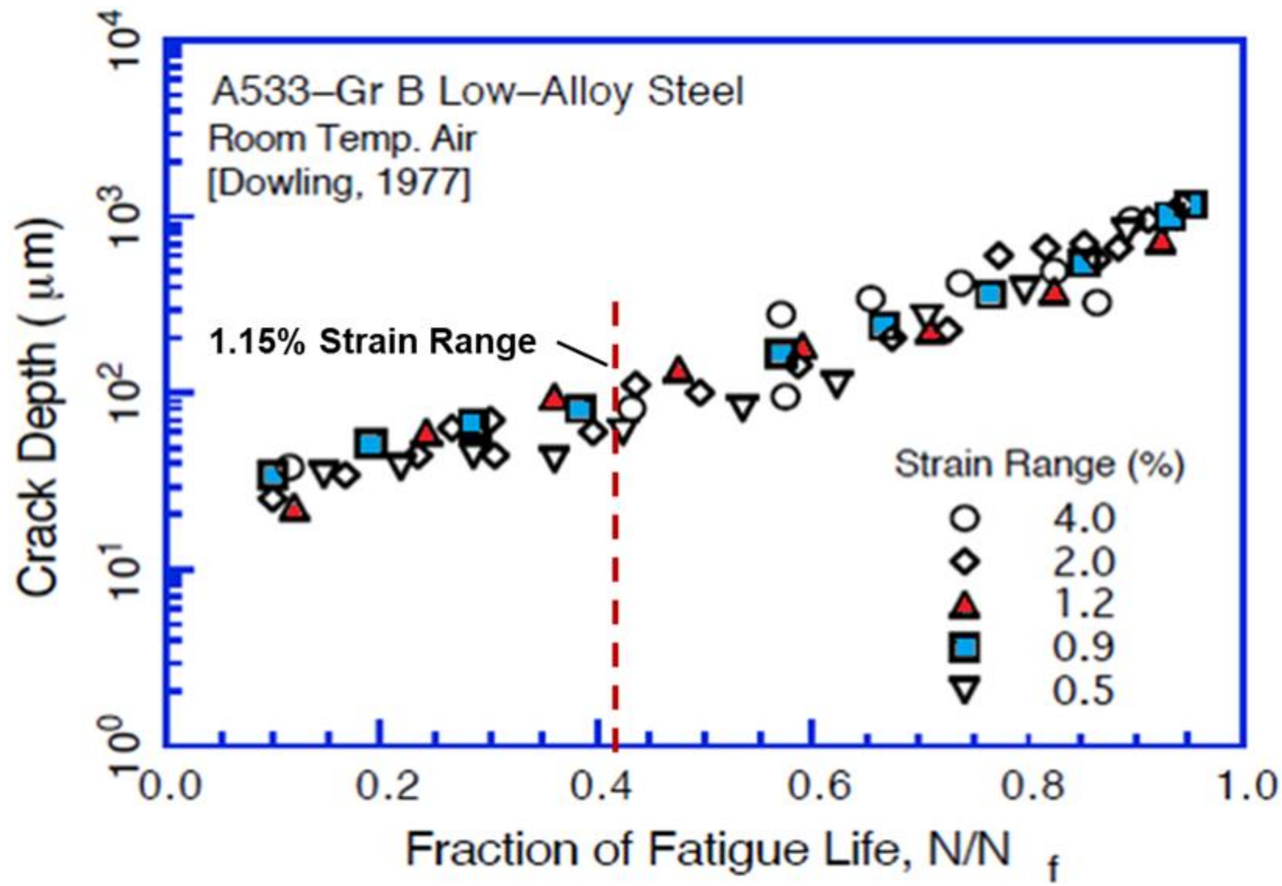
25% load-drop crack depth of 0.118 in. (3-mm) is associated with a 0.304 in. (7.72 mm) specimen gauge diameter that represents the median NUREG/CR-6909 test specimen size

CS, LAS, SS Stage I Life for 1.150% Strain

Stage I Life $\Delta\varepsilon$ = 1.150%	**CS**		**LAS**		**SS**	
Pin Diameter, inch (mm)	0.304 (7.72)		0.304 (7.72)		0.304 (7.72)	
Initial Flaw Depth, *a*, inch (mm)	0.008 (0.203)		0.008 (0.203)		0.008 (0.203)	
25% Load Drop Crack Depth, inch (mm)	0.118 (3.00)		0.118 (3.00)		0.118 (3.00)	
Initial Aspect Ratio, *L/a*	2		2		2	
Elastic Modulus, *E*, ksi (MPa)	29,400 (202,700)		29,000 (199,900)		28,300 (195,122)	
Temperature, °F (°C)	77 (25)		77 (25)		77 (25)	
$\Delta\varepsilon$, %	1.150		1.150		1.150	
NUREG/CR-6909 Rev. 1 50|50 *S-N* Life, *N*	3,321		2,982		4,313	
Stage II Membrane Life at 0.118 in. (3 mm) Crack Depth, N_{II}	1,964		1,733		2,069	
Stage I Membrane Life ($N_I = N - N_{II}$)	**1,357**	**40.9%**	**1,249**	**41.9%**	**2,244**	**52.0%**

LAS Stage 1 Life: 1.150% Strain Range (ii)

Low Alloy Steel	
Strain Range	**Stage I (cycles)**
0.48%	35,202
0.80%	3,797
1.15%	1,249
1.50%	627
2.00%	320
2.50%	197



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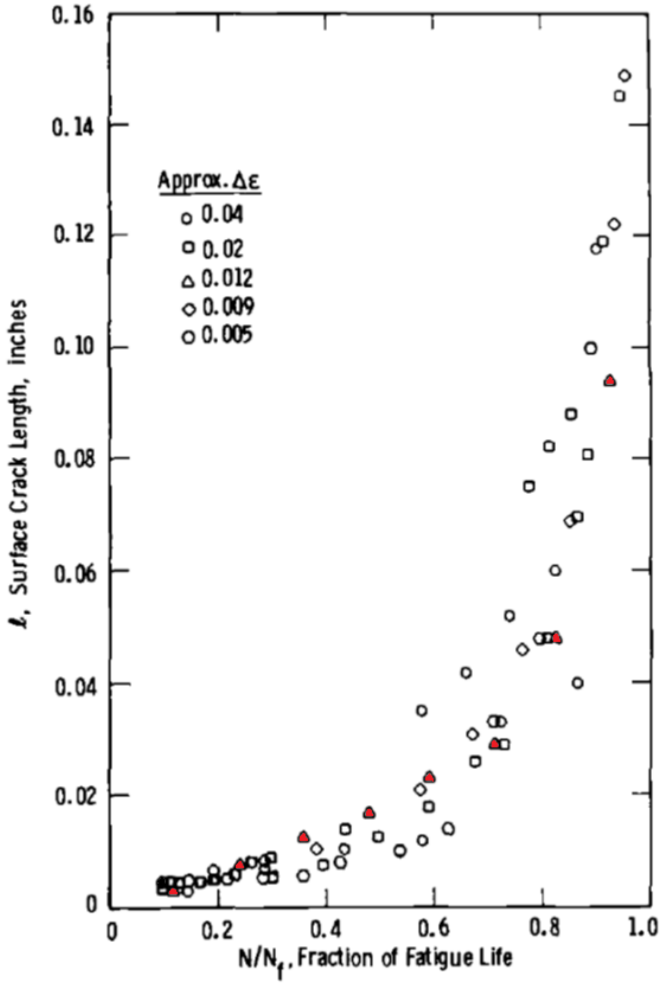
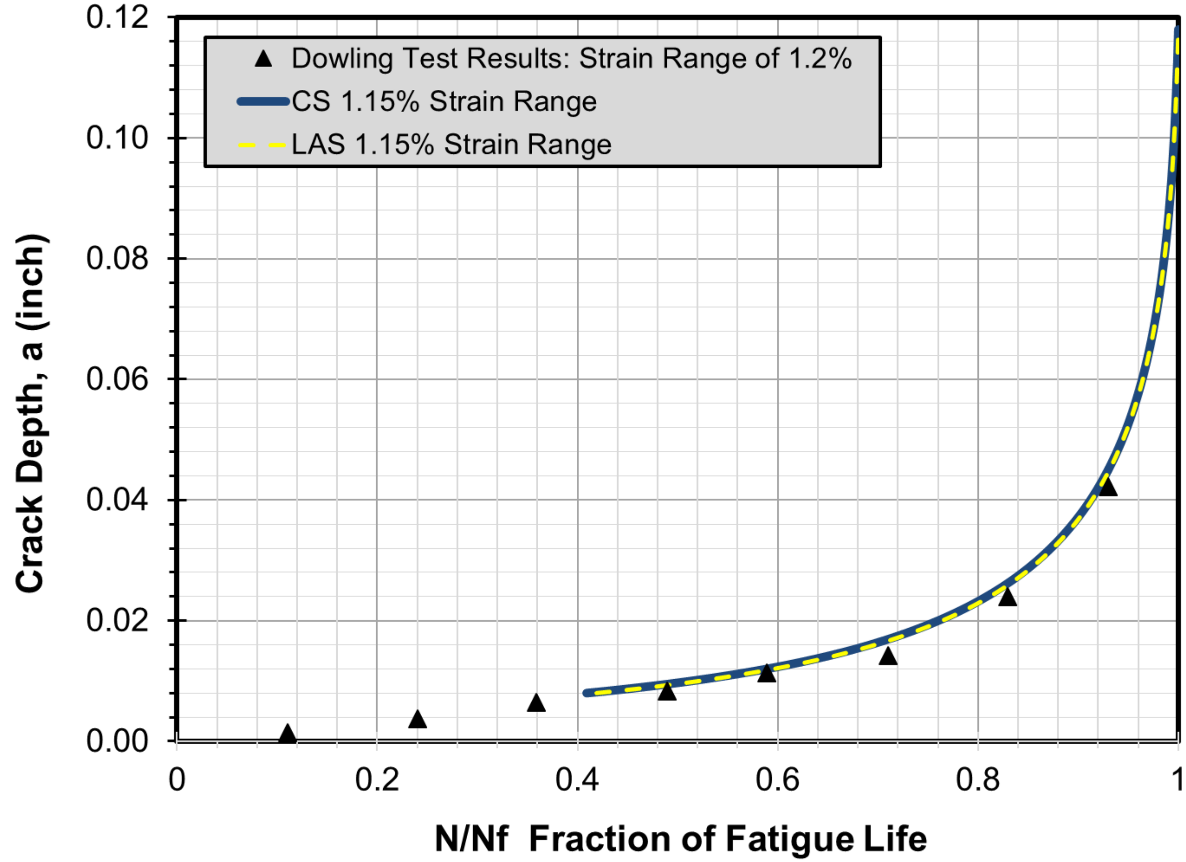
Pin Crack Depth vs Life Fraction Comparison (Damiani and Smith)





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STAGE II LIFE FOR A CYLINDER

Stage II Life (i)

- Crack growth of a mechanically small crack (0.008 in.) to a crack depth associated with a 25% load drop
- Stage II deterministic crack growth calculations were performed using the NRC PRAISE computer code
- PRAISE was modified to include a best estimate (50/50) of the C/LAS crack relationship in ASME Section XI Non-Mandatory Appendix C
- The alternating stress intensity was corrected for elastic-plastic material response in the HIGH strain LOW cycle region.

Stage II Life (ii)

- PRAISE was modified to include a best estimate version of the C, LAS and SS crack growth relationships in room temperature air
- The elastic alternating stress intensity, ΔKI, is subsequently adjusted for elastic-plastic material response in the high-strain low-cycle region at the crack “a”-tip and “b”-tip.
- Elastic J-integral range, $\Delta J_{elastic}$, was obtained from linear elastic finite element analyses, and the elastic-plastic J-integral range, $\Delta J_{elastic\text{-}plastic}$, was computed by performing elastic-plastic finite element analyses

C/LAS Stage II Life

$$\frac{da}{dN} = C_0(\Delta K_I)^n$$

$$n = 3.07$$

$$C_0 = C_{50} \cdot S$$

$$C_{50} = \frac{1.99 \times 10^{-10}}{1.24} = 1.605 \times 10^{-10}$$

$$S = \frac{25.72}{(2.88 - R)^{3.07}}$$

$$R\text{-}ratio = \Delta K_{min} / \Delta K_{max} = \textbf{-1}$$

$$\Delta K_I = (K_{max} - K_{min})$$

$$\Delta K_I' = (K_{max} - K_{min}) \times \frac{\Delta K_J}{\Delta K_I}$$

Carbon Steel Plastic Correction Factor (ΔKJ/ΔKI)		
Strain Range	**A-TIP**	**B-TIP**
0.48%	$y = 0.285x^2 - 0.0361x + 0.9942$	$y = 0.1227x^2 + 0.0156x + 0.7425$
0.80%	$y = 0.3082x^2 - 0.045x + 0.8341$	$y = 0.0888x^2 + 0.0227x + 0.5801$
1.15%	$y = 0.2845x^2 - 0.0436x + 0.7295$	$y = 0.0823x^2 + 0.018x + 0.4725$
1.50%	$y = 0.2116x^2 + 0.0041x + 0.6505$	$y = 0.2398x^2 - 0.0839x + 0.4101$
2.00%	$y = 0.1222x^2 + 0.0293x + 0.5851$	$y = 0.0625x^2 - 0.009x + 0.3368$
2.50%	$y = 0.2527x^2 - 0.0535x + 0.5332$	$y = 0.0711x^2 - 0.0239x + 0.2785$

Low Alloy Steel Plastic Correction Factor (ΔKJ/ΔKI)		
Strain Range	**A-TIP**	**B-TIP**
0.48%	$y = 0.2814x^2 - 0.0324x + 1.0406$	$y = 0.1595x^2 - 0.0105x + 0.7752$
0.80%	$y = 0.3464x^2 - 0.0259x + 0.8686$	$y = 0.0877x^2 + 0.0405x + 0.591$
1.15%	$y = 0.3848x^2 - 0.0506x + 0.7721$	$y = 0.0824x^2 + 0.0088x + 0.4863$
1.50%	$y = 0.2761x^2 - 0.0042x + 0.6927$	$y = 0.0022x^2 + 0.0341x + 0.4053$
2.00%	$y = 0.3949x^2 - 0.0662x + 0.6246$	$y = 0.0345x^2 + 0.0513x + 0.315$
2.50%	$y = 0.3561x^2 - 0.0506x + 0.5707$	$y = 0.0268x^2 + 0.0263x + 0.2712$

SS Stage II Life

$$\frac{da}{dN} = C_0(\Delta K_I)^n$$

$$n = 3.07$$

$$C_0 = C_{50} \cdot S$$

$$C_{50} = \frac{1.99 \times 10^{-10}}{1.24} = 1.605 \times 10^{-10}$$

$$S = \frac{25.72}{(2.88 - R)^{3.07}}$$

$$R\text{-}ratio = \Delta K_{min} / \Delta K_{max} = -1$$

$$\Delta K_I = (K_{max} - K_{min})$$

$$\Delta K_I' = (K_{max} - K_{min}) \times \frac{\Delta K_J}{\Delta K_I}$$

Stainless Steel Plastic Correction Factors (DKJ/DKI)		
Strain Range	A-TIP	B-TIP
0.48%	$\frac{\Delta K_J}{\Delta K_I} = 0.0564(a/t)^2 - 0.0025(a/t) + 0.7253$	$\frac{\Delta K_J}{\Delta K_I} = 0.0478(a/t)^2 + 0.0023(a/t) + 0.6072$
0.80%	$\frac{\Delta K_J}{\Delta K_I} = 0.0734(a/t)^2 - 0.0089(a/t) + 0.6542$	$\frac{\Delta K_J}{\Delta K_I} = 0.0642(a/t)^2 - 0.0040(a/t) + 0.5305$
1.15%	$\frac{\Delta K_J}{\Delta K_I} = 0.083(a/t)^2 - 0.0093(a/t) + 0.6068$	$\frac{\Delta K_J}{\Delta K_I} = 0.0707(a/t)^2 - 0.0091(a/t) + 0.4768$
1.50%	$\frac{\Delta K_J}{\Delta K_I} = 0.0702(a/t)^2 + 0.0004(a/t) + 0.5697$	$\frac{\Delta K_J}{\Delta K_I} = 0.0086(a/t)^2 + 0.0191(a/t) + 0.4302$
2.00%	$\frac{\Delta K_J}{\Delta K_I} = 0.0660(a/t)^2 + 0.0002(a/t) + 0.5376$	$\frac{\Delta K_J}{\Delta K_I} = 0.0085(a/t)^2 + 0.0161(a/t) + 0.3848$
2.50%	$\frac{\Delta K_J}{\Delta K_I} = 0.0629(a/t)^2 + 0.0009(a/t) + 0.5138$	$\frac{\Delta K_J}{\Delta K_I} = 0.0251(a/t)^2 + 0.0027(a/t) + 0.3468$

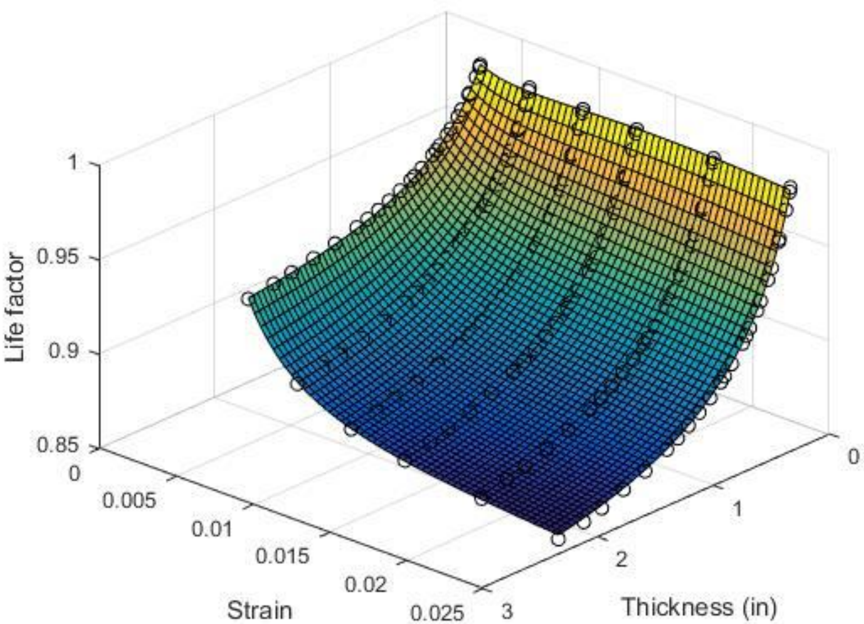
LIFE & GRADIENT FACTOR REGRESSIONS

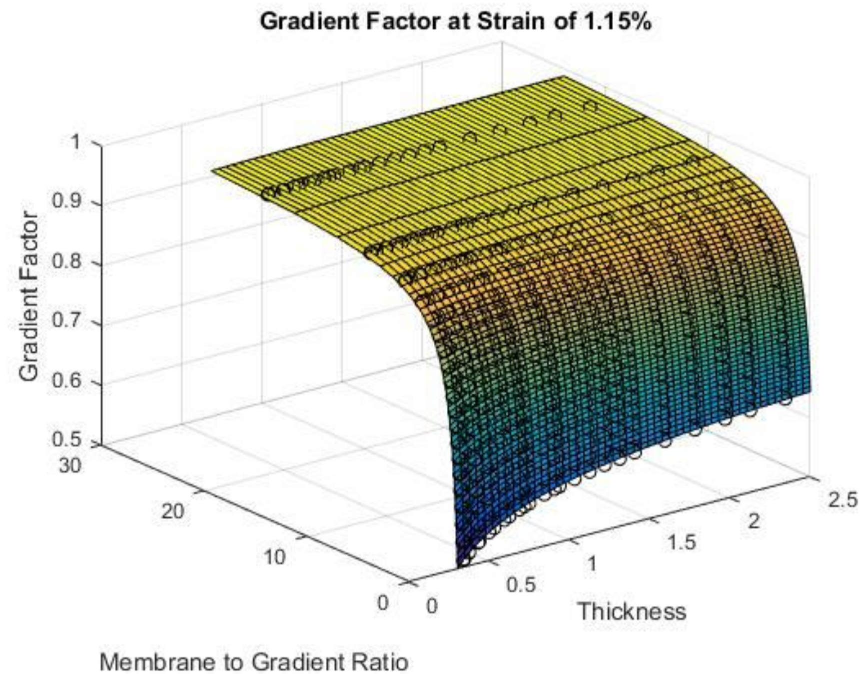
Life & Gradient Factor Data

- Carbon/Low Alloy Steel and Stainless Steel
  - Room temperature air environment
- Cyclic Loads:
  - % Strain Range (ε) = 0.48, 0.8, 1.15, 1.5, 2, 2.5
- Nominal Pipe Sizes:
  - NPS 2, 2.5, 3, 4, 5, 6, 8, 10, 12, 14, 16,18, 20, 22, and 24
- Pipe Schedules:
  - 80 and 160
- Pipe Thickness Range:
  - 0.154 in. to 2.344 in.
- Data
  - 3780 Life Factors
  - 3780 Gradient Factors

C/LAS Life & Gradient Factor Data* (ii)

* Carbon steel data shown





$$LF = \frac{N_{3mm}}{N_{25\%}} = \frac{N_I + N_{II(3mm)}}{\left(N_I + N_{II(25\%)}\right)}$$

$$GF = \frac{(N_I + N_{II})_{Membrane}}{(N_I)_{Membrane} + (N_{II})_{Gradient}}$$

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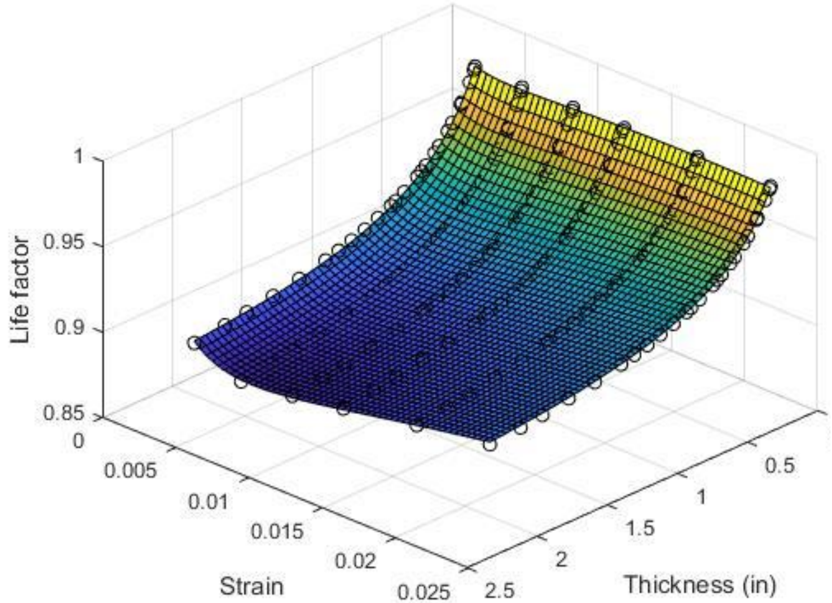
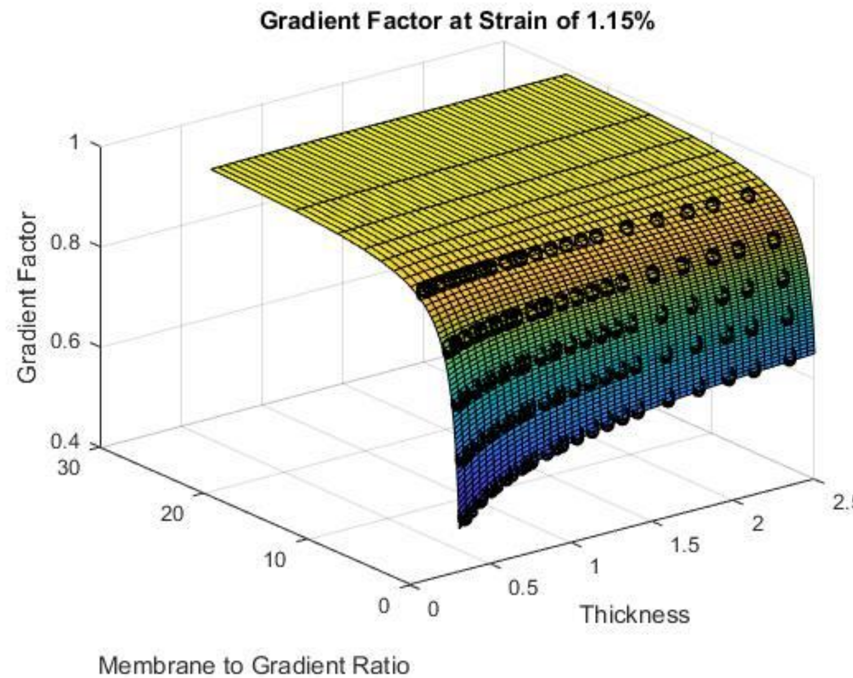
SS Life & Gradient Factor Data* (ii)

* Stainless steel data shown





$$LF = \frac{N_{3mm}}{N_{25\%}} = \frac{N_I + N_{II(3mm)}}{\left(N_I + N_{II(25\%)}\right)}$$

$$GF = \frac{(N_I + N_{II})_{Membrane}}{(N_I)_{Membrane} + (N_{II})_{Gradient}}$$

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C/LAS Life Factor Regression Models

$$LF = \left(A + B \cdot t^* + C \cdot \left(t^*\right)^2 + D \cdot \left(t^*\right)^3 \right) / 1000$$

Carbon Steel

$$A = 52.295 - 590.26 \times \varepsilon^* - 139.14 \times \left(\varepsilon^*\right)^2 - 11.250 \times \left(\varepsilon^*\right)^3$$

$$B = 77.704 + 75.874 \times \varepsilon^* + 10.331 \times \left(\varepsilon^*\right)^2$$

$$C = 37.423 + 5.2371 \times \varepsilon^*$$

$$D = 0.74926$$

Low Alloy Steel

$$A = 180.96 - 545.24 \times \varepsilon^* - 138.58 \times \left(\varepsilon^*\right)^2 - 11.933 \times \left(\varepsilon^*\right)^3$$

$$B = 220.80 + 142.17 \times \varepsilon^* + 17.919 \times \left(\varepsilon^*\right)^2$$

$$C = 35.254 + 4.8640 \times \varepsilon^*$$

$$D = 1.5080$$

where:

$$t^* = \ln(t)$$

$$\varepsilon^* = \ln\left(\varepsilon_{range}\right)$$

$$t = Thickness\ (in.)$$

SS Life Factor Regression Models

$$LF = \left(A + B \cdot t^* + C \cdot \left(t^*\right)^2 + D \cdot \left(t^*\right)^3 \right) / 1000$$

Stainless Steel

$$A = 600.28 - 303.60 \times \varepsilon^* - 84.289 \times \left(\varepsilon^*\right)^2 - 7.3023 \times \left(\varepsilon^*\right)^3$$

$$B = 195.04 + 103.10 \times \varepsilon^* + 11.053 \times \left(\varepsilon^*\right)^2$$

$$C = 4.2302 - 2.0595 \times \varepsilon^*$$

$$D = -0.87079$$

where:

$$t^* = \ln(t)$$

$$\varepsilon^* = \ln\left(\varepsilon_{range}\right)$$

$$t = Thickness\ (in.)$$

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C/LAS Gradient Factor Regression Models

$$GF = 1 - (1 - \mathbf{M}) \cdot [A + B + C + D] / 1000$$

Carbon Steel

$$A = -486.03 - 124.65 \cdot t^* + 60.446 \cdot \mathbf{M} - 240.41 \cdot \mathbf{B} - 477.06 \cdot \varepsilon^*$$

$$B = 15.873 \cdot \left(t^*\right)^2 + 25.591 \times t^* \cdot \mathbf{M} + 28.354 \cdot t^* \cdot \mathbf{B} - 14.676 \cdot t^* \cdot \varepsilon^*$$

$$C = 26.691 \cdot \mathbf{M}^2 - 229.76 \cdot \mathbf{M} \cdot \mathbf{B} + 31.654 \cdot \mathbf{M} \cdot \varepsilon^*$$

$$D = 12.153 \times \mathbf{B}^2 - 27.369 \times \mathbf{B} \cdot \varepsilon^* - 62.559 \cdot \left(\varepsilon^*\right)^2$$

Low Alloy Steel

$$A = -1254.3 - 131.44\left(t^*\right) + 42.095(\mathbf{M}) - 263.20(\mathbf{B}) - 831.82\left(\varepsilon^*\right)$$

$$B = 15.484\left(t^*\right)^2 + 24.215\left(t^*\right)(\mathbf{M}) + 28.095\left(t^*\right)(\mathbf{B}) - 16.569\left(t^*\right)\left(\varepsilon^*\right)$$

$$C = 27.324(\mathbf{M})^2 - 221.22(\mathbf{M})(\mathbf{B}) + 27.642(\mathbf{M})\left(\varepsilon^*\right)$$

$$D = 10.828(\mathbf{B})^2 - 33.048(\mathbf{B})\left(\varepsilon^*\right) - 103.34\left(\varepsilon^*\right)^2$$

where:

$$\mathbf{M} = \frac{\sigma_m}{\sigma_m + \sigma_b + \sigma_g}$$

$$\mathbf{B} = \frac{\sigma_b}{\sigma_m + \sigma_b + \sigma_g}$$

and

σ_m = Uniform membrane stress

σ_b = Linear bending stress

σ_g = Non-linear gradient stress

$t^* = \ln(t) \quad \varepsilon^* = \ln\left(\varepsilon_{range}\right)$

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SS Gradient Factor Regression Models

$$GF = 1 - (1 - \mathbf{M}) \cdot [A + B + C + D] / 1000$$

Stainless Steel

$$A = -914.68 - 45.507 \cdot t^* - 155.40 \cdot \mathbf{M} - 40.507 \cdot \mathbf{B} - 559.38 \cdot \varepsilon^*$$

$$B = 19.835 \cdot (t^*)^2 + 33.757 \times t^* \cdot \mathbf{M} + 33.359 \cdot t^* \cdot \mathbf{B} + 6.1255 \cdot t^* \cdot \varepsilon^*$$

$$C = 32.740 \cdot \mathbf{M}^2 - 202.8 \cdot \mathbf{M} \cdot \mathbf{B} - 13.47 \cdot \mathbf{M} \cdot \varepsilon^*$$

$$D = 24.029 \times \mathbf{B}^2 + 20.685 \times \mathbf{B} \cdot \varepsilon^* - 59.375 \cdot (\varepsilon^*)^2$$

where:

$$\mathbf{M} = \frac{\sigma_m}{\sigma_m + \sigma_b + \sigma_g}$$

$$\mathbf{B} = \frac{\sigma_b}{\sigma_m + \sigma_b + \sigma_g}$$

and

σ_m = Uniform membrane stress

σ_b = Linear bending stress

σ_g = Non-linear gradient stress

$t^* = \ln(t) \quad \varepsilon^* = \ln(\varepsilon_{range})$

EXAMPLE

NPS 10 Schedule 80 Reducing Elbow

BWR 4 LPCS 10 x 12 Reducing Elbow

- 60 year design fatigue usage calculation at a Schedule 80 10" X 12" reducing elbow in a Low Pressure Core Spray (LPCS) system
- Original calculation performed according to stress analysis procedures specified in ASME III NB-3600
- The highest fatigue usage was located at Node 330 where a ¾" socket-welded elbolet is attached to Schedule 80 10" X 12" reducing elbow
- The reducing elbow thickness at the location is 0.594".
- 60 year fatigue usage estimates are corrected the component thickness and the presence of through-wall stress gradients.

Node 330 60-yr Air and Water Fatigue Usages

Node 330 60-year ASME Section III Air and NUREG/CR-6583 Water Fatigue Usages

Load Pair	60-Year Cycles	ASME Eq. 10 ksi (MPa)		ASME Eq. 11 ksi (MPa)		K_e	S_{alt} ksi (MPa)		U_{air}	F_{en}	U_{water}
4-6	10	92.405	(637.132)	184.000	(1,268.680)	2.410	221.675	(1,528.449)	0.126	5.972	0.752
11-12	50	42.349	(291.996)	76.625	(528.329)	1.000	38.313	(264.1681)	0.005	1.74	0.009
11-14	200	41.718	(287.646)	75.365	(519.642)	1.000	37.683	(259.8243)	0.019	1.74	0.033
4-5	55	29.828	(205.664)	52.698	(363.353)	1.000	26.439	(182.2969)	0.001	7.33	0.007
5-14	155	29.525	(203.575)	52.571	(362.477)	1.000	26.285	(181.2351)	0.004	1.74	0.007
								Totals:	**0.155**		**0.809**

Node 330 ASME Equation 11 and ASME Equation 14 Stresses (w/o DISCON)

Load Pair	Pressure ksi (MPa)		Moment ksi (MPa)		Gradient ksi (MPa)		S_p ksi (MPa)		K_e	S_{alt} ksi (MPa)		ε_{alt} %
4-6	48.456	(334.104)	14.559	(100.384)	80.161	(552.710)	143.176	(987.199)	2.410	172.527	(1,189.574)	0.575
11-12	45.743	(315.398)	30.882	(212.931)	0.000	(0.000)	76.625	(528.329)	1.000	38.313	(264.168)	0.128
11-14	45.743	(315.398)	29.622	(204.244)	0.000	(0.000)	75.365	(519.642)	1.000	37.683	(259.824)	0.126
4-5	39.424	(271.828)	13.274	(91.524)	0.000	(0.000)	52.698	(363.353)	1.000	26.349	(181.676)	0.088
5-14	36.711	(253.122)	15.860	(109.355)	0.000	(0.000)	52.571	(362.477)	1.000	26.286	(181.242)	0.088

Node 330 Membrane-to-Gradient Ratios

Node 330 Membrane-to-Gradient Stress Ratios

Load Pair	Membrane σ_m ksi (MPa)		Thru-wall σ_b ksi (MPa)		Gradient σ_g ksi (MPa)		$\sigma_m/(\sigma_b+\sigma_g)$
4-6	61.406	(423.394)	1.609	(11.094)	80.161	(552.710)	0.7510
11-12	73.212	(504.797)	3.413	(23.533)	0.000	(0.000)	21.452
11-14	72.091	(497.067)	3.274	(22.574)	0.000	(0.000)	22.022
4-5	51.231	(353.238)	1.467	(10.115)	0.000	(0.000)	34.924
5-14	50.818	(350.39)	1.753	(12.087)	0.000	(0.000)	28.994

Node 330 Stage I Life

Node 330 Stage I Life Calculation for a 0.304" Solid Pin

Stage 1 Life ($\Delta\varepsilon$ = 1.150%)	**Carbon Steel**	
Pin Diameter, inch (mm)	0.304 (7.72)	
Initial Flaw Depth, *a*, inch (mm)	0.008 (0.203)	
25% Load Drop Crack Depth, inch (mm)	0.118 (3.00)	
Initial Aspect Ratio, *L/a*	2	
Elastic Modulus, ksi (MPa)	30,000 (206,800)	
Temperature, °F (°C)	77 (25)	
$\Delta\varepsilon$, %	1.15	
NUREG/CR-6909 R1 50|50 S-N Life (*N*)	3,321	
Stage II Membrane Life at 3-mm Crack Depth (N_{II})	1,964	
Stage 1 Membrane Life ($N_I = N - N_{II}$)	**1,357**	**40.9%**

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Node 330 LF and GF Calculation

Node 330 LF and GF Calculation for NPS 10 Schedule 80 Pipe (CS)

Node 330 Load Set 4-6 *LF* and *GF*	**Membrane**	**σ_m/σ_g = 0.751**
Thickness, inch (mm) (wall thickness for 10" sch. 80 pipe)	0.594 (15.088)	0.594 (15.088)
Initial Flaw Depth, *a*, inch (mm)	0.008 (0.203)	0.008 (0.203)
25% Load Drop Crack Depth, in. (mm) (interpolated from Table 6-1 for 0.594" thickness)	0.231 (5.867)	0.231 (5.867)
Initial Aspect Ratio, *L/a*	2	2
Elastic Modulus, ksi (MPa)	30,000 (206,800)	30,000 (206,800)
Temperature, °F (°C)	77 (25)	77 (25)
$\Delta\varepsilon$, %	1.150	1.150
Stage 1 Membrane Life, N_I	1,358	1,358
Stage 2 Life, $N_{II(3mm)}$	3,690	3,780
Stage 2 Life, $N_{II(25\%)}$	3,995	5,653
Gradient Factor, *GF* (Eq. 9-2)	1.000	0.764
Life Factor, *LF* (Eq. 9-1)	0.943	0.943
LF* x *GF	**0.943**	**0.720**

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Node 330: C/LAS/SS Life Factor

$$LF = \left(A + B \cdot t^* + C \cdot \left(t^*\right)^2 + D \cdot \left(t^*\right)^3 \right) / 1000$$

Carbon Steel	Low Alloy Steel	Stainless Steel
$A = 915.309$	$A = 1732.397$	$A = 925.461$
$B = -55.105$	$B = -35.2658$	$B = -44.948$
$C = 14.037$	$C = -56.8178$	$C = 13.427$
$D = 0.74926$	$D = -1246.04$	$D = -0.871$
LF = 0.9440	**LF = 0.9476**	**LF = 0.9526**

where:

$t^* = \ln(t)$

$\varepsilon^* = \ln(\varepsilon_{range})$

$t = Thickness\ (in.)$

and,

$t^* = -0.5209$

$\varepsilon^* = -4.4654$

Node 330: C/LAS/SS Gradient Factor

$$GF = 1 - (1 - \mathbf{M}) \cdot [A + B + C + D] / 1000$$

Carbon Steel	Low Alloy Steel	Stainless Steel
$A = 1732.397$	$A = 2543.655$	$A = 1539.775$
$B = -35.2658$	$B = -39.9132$	$B = 11.894$
$C = -56.8178$	$C = -48.9774$	$C = 30.846$
$D = -1246.04$	$D = -2059.01$	$D = -1184.960$
$\mathbf{GF = 0.7634}$	$\mathbf{GF = 0.7735}$	$\mathbf{GF = 0.7730}$

where:

$\mathbf{M} = 0.4289$

$\mathbf{B} = 0.0112$

and

$\sigma_m = 61.406$ ksi

$\sigma_b = 1.609$ ksi

$\sigma_g = 80.161$ ksi

$t^* = -0.5209$

$\varepsilon^* = -4.4654$

CS/LAS/SS LF & GF Comparisons

LF and GF Comparison for CS at 1.15% Strain Range

	pcPRAISE	Regression	% error
Life Factor, *LF*	0.9430	0.9440	0.1060
Gradient Factor, *GF*	0.7635	0.7634	-0.0131
LF x *GF*	0.7200	0.7206	0.0929

Note: The CS LF and GF regressions agree with the pcPRAISE solution to within 0.11%.

LF and GF Comparison for LAS at 1.15% Strain Range

	pcPRAISE	Regression	% error
Life Factor, *LF*	0.9471	0.9476	0.0528
Gradient Factor, *GF*	0.7732	0.7735	0.0388
LF x *GF*	0.7323	0.7330	0.0916

Note: The LAS LF and GF regressions agree with the pcPRAISE solution to within 0.10%.

LF and GF Comparison for SS at 1.15% Strain Range

	pcPRAISE	Regression	% error
Life Factor, *LF*	0.9523	0.9526	0.0315
Gradient Factor, *GF*	0.7729	0.7730	0.0129
LF x *GF*	0.7360	0.7364	0.0444

Note: The SS LF and GF regressions agree with the pcPRAISE solution to within 0.05%.

Case N-X-0
Life and Gradient Factors for Section III Piping Fatigue Analyses

Inquiry: What alternative to the rules of XIII-3520(e)[1] may be used for carbon steel, low alloy steel, and stainless-steel piping fatigue analyses to account for both thickness and the presence of non-uniform through-thickness stress distributions when using the uniaxial fatigue design curves for carbon/low alloy steels in Figures I-9.1 or I-9.1M or stainless steels in Figures I-9.2 or I 9.2M?

Reply: It is the opinion of the Committee that as an alternative to *Step 5* of the rules in XIII-3520(e)[1], piping fatigue analyses may be evaluated in accordance with the following requirements to account for the component thickness and the presence of non-uniform through-thickness stress distributions when using the uniaxial fatigue design curves for carbon/low alloy steels in Figures I-9.1 or I-9.1M or stainless steels in Figures I-9.2 or I 9.2M.

1000 INTRODUCTION

1100 Scope

This Case provides a method to perform fatigue usage evaluations for piping components that considers the presence of non-uniform through-thickness stress distributions when using the uniaxial fatigue design curves for carbon/low alloy steels in Figures I-9.1 or I-9.1M, or stainless steels in Figures I-9.2 or I-9.2M. The fatigue usage life and gradient factor evaluation procedures and acceptance criteria are provided in -2000. The evaluations shall be documented in accordance with the provisions of -3000.

1200 Nomenclature

The following symbols are used in this Case:

GF_i = ith load set pair Gradient Factor

LF_i = ith load set pair Life Factor

A = Influence coefficient

B = Influence coefficient

C = Influence coefficient

D = Influence coefficient

i = load set pair number

U_i = ith load pair usage factor

U = total cumulative usage factor

t = thickness, in. (mm)
for 0.218 in. (5.5 mm) $\leq t \leq$ 2.344 in. (59.5 mm)

t^* = ln(t)

B = ith fractional linear through-thickness bending stress
$= \sigma_b / (\sigma_m + \sigma_b + \sigma_g)$

M = ith fractional uniform membrane stress
$= \sigma_m / (\sigma_m + \sigma_b + \sigma_g)$

ε_i = ith load set pair strain range for $0.0048 \leq \varepsilon_i \leq 0.025$

ε_i^* = ln (ε_i)

σ_m = ith uniform membrane stress, ksi (MPa)

σ_b = ith linear through-thickness bending stress, ksi (MPa)

σ_g = ith non-linear through-thickness stress, ksi (MPa)

[1] NB-3222.4(e)(5) in editions earlier than the 2017 Edition.

2000 FATIGUE LIFE AND GRADIENT FACTOR CORRECTION EVALUATION

The fatigue life factor (LF) accounts for the increased cyclic life associated with component wall thicknesses that differ from standard fatigue test specimens with an average diameter of 0.304 in. (7.72 mm). The fatigue gradient factor (GF) accounts for the increased fatigue life associated with the presence of through-thickness stress gradients. These factors are applied to load pair-specific cumulative usage factors, U_i

2100 Scope

The evaluation method uses cumulative usage factor $U = U_1, U_2, U_3, \ldots, U_n$ determined in the component fatigue evaluation in XIII-3520(e)[1].

As an alternative to *Step 5* of XIII-3520(e)[1], the cumulative usage factor, considering the life and gradient factors, is calculated as the following:

$$U = U_1 \cdot LF_1 \cdot GF_1 + U_2 \cdot LF_2 \cdot GF_2 + \ldots + U_n \cdot LF_n \cdot GF_n$$

2200 Determination of Life Factor

$$LF_i = \left(A + B \cdot t^* + C \cdot \left(t^*\right)^2 + D \cdot \left(t^*\right)^3 \right) / 1000$$

The influence coefficients A, B, C, and D are defined in 2210 and 2220 depending on material type. The LF_i value shall not exceed 1.0.

2210 Carbon Steel

$$A = 413.69 - 363.1\left(\varepsilon^*\right) - 91.483\left(\varepsilon^*\right)^2 - 7.845\left(\varepsilon^*\right)^3$$

$$B = 112.26 + 88.557\left(\varepsilon^*\right) + 11.256\left(\varepsilon^*\right)^2$$

$$C = 33.021 + 4.0481\left(\varepsilon^*\right)$$

$$D = 0.7011$$

2220 Low Alloy Steel

$$A = 630.5 - 245.71\left(\varepsilon^*\right) - 71.919\left(\varepsilon^*\right)^2 - 6.9736\left(\varepsilon^*\right)^3$$

$$B = 226.16 + 141.59\left(\varepsilon^*\right) + 17.521\left(\varepsilon^*\right)^2$$

$$C = 35.286 + 4.9246\left(\varepsilon^*\right)$$

$$D = 0.97908$$

2230 Austenitic Stainless Steel

$$A = 600.28 - 303.60 \times \varepsilon^* - 84.289 \times \left(\varepsilon^*\right)^2 - 7.3023 \times \left(\varepsilon^*\right)^3$$

$$B = 195.04 + 103.10 \times \varepsilon^* + 11.053 \times \left(\varepsilon^*\right)^2$$

$$C = 4.2302 - 2.0595 \times \varepsilon^*$$

$$D = -0.87079$$

2300 Determination of Gradient Factor

$$GF_i = 1 - (1 - \mathbf{M}) \cdot \left[A + B + C + D\right] / 1000$$

The influence coefficients A, B, C, and D are defined in 2310 and 2320 depending on material type. The GF_i value shall not exceed 1.0.

2310 Carbon Steel

$$A = -418.72 - 109.46\left(t^*\right) + 64.519(\mathbf{M}) - 202.78(\mathbf{B}) - 430.53\left(\varepsilon^*\right)$$

$$B = 16.685\left(t^*\right)^2 + 20.034\left(t^*\right)(\mathbf{M}) + 28.389\left(t^*\right)(\mathbf{B}) - 10.861\left(t^*\right)\left(\varepsilon^*\right)$$

$$C = 30.297(\mathbf{M})^2 - 250.67(\mathbf{M})(\mathbf{B}) + 31.513(\mathbf{M})\left(\varepsilon^*\right)$$

$$D = 10.760(\mathbf{B})^2 - 18.584(\mathbf{B})\left(\varepsilon^*\right) - 54.736\left(\varepsilon^*\right)^2$$

2320 Low Alloy Steel

$$A = -1046.8 - 124.29\left(t^*\right) + 44.431(\mathbf{M}) - 244.38(\mathbf{B}) - 728.12\left(\varepsilon^*\right)$$

$$B = 15.803\left(t^*\right)^2 + 23.969\left(t^*\right)(\mathbf{M}) + 28.18\left(t^*\right)(\mathbf{B}) - 14.861\left(t^*\right)\left(\varepsilon^*\right)$$

$$C = 34.088(\mathbf{M})^2 - 225.12(\mathbf{M})(\mathbf{B}) + 28.967(\mathbf{M})\left(\varepsilon^*\right)$$

$$D = 11.678(\mathbf{B})^2 - 28.572(\mathbf{B})\left(\varepsilon^*\right) - 90.494\left(\varepsilon^*\right)^2$$

2330 Austenitic Stainless Steel

$$A = -914.68 - 45.507 \cdot t^* - 155.40 \cdot \mathbf{M} - 40.507 \cdot \mathbf{B} - 559.38 \cdot \varepsilon^*$$

$$B = 19.835 \cdot \left(t^*\right)^2 + 33.757 \times t^* \cdot \mathbf{M} + 33.359 \cdot t^* \cdot \mathbf{B} + 6.1255 \cdot t^* \cdot \varepsilon^*$$

$$C = 32.740 \cdot \mathbf{M}^2 - 202.8 \cdot \mathbf{M} \cdot \mathbf{B} - 13.47 \cdot \mathbf{M} \cdot \varepsilon^*$$

$$D = 24.029 \times \mathbf{B}^2 + 20.685 \times \mathbf{B} \cdot \varepsilon^* - 59.375 \cdot \left(\varepsilon^*\right)^2$$

3000 RECORDS AND REPORTS

3100 Scope

This section contains records and report provisions evaluations specified in -2000.

3200 Evaluation Records and Reports

The evaluations specified in -2000 shall be documentec the Design Report.

DISCUSSION

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