ME 4223 – Welding Engineering II – Fall 2019

Location – Louisiana State University (PTH 1244)

Times – Tuesday, November 5th and Thursday November 7th, 2019 (9:00am – 10:20am)

Professor – Dr. W.A. Wahab

Practical Aspects of a Welding Engineer

Course Guest Lecturer – Brent M. Saba, PE-ME/MT

Saba Metallurgical and Plant Engineering Services, LLC

Lecture Outline

Day 1

I. Introductions
II. Motivations

III. Static Weld Designs
1. ASME Section VIII Div. 1 (Code Formula)
2. ASME Section VIII Div. 2 (Part 4 Design by Formula)
3. Code Weld Types
4. Weld Joint Efficiencies
5. ASME Section VIII Div. 2 Part 5 (Finite Element Analysis Rules)
    a. Elastic Stress Analysis Method
    b. Limit load Analysis Method
    c. Elastic-Plastic Stress Analysis Method
    d. Protection Against Local Failure

IV. Cyclic Loading (Fatigue) Weld Designs
1. Fatigue Assessments – Elastic Stress Analysis and Equivalent Stresses [Crack Initiation Model]
2. Fatigue Assessments – Elastic-Plastic Stress Analysis and Equivalent Strains [Crack Initiation Model]
3. Fatigue Assessments – Elastic Analysis and Structural Stress [Crack Propagation Model]

V. Brittle Failure
a. ASME Section VIII Div. 1
b. WRC 562 (Recommendations for Establishing the Minimum Pressurization Temperature (MPT) for Equipment

Day 2

VI. Fitness-for-Service

1. ASME FFS-1 / API-579
2. Crack Growth Models [Paris Equations-Hand Calculations]
3. Determining Stress Intensity Factors (K) and J-Integral using Finite Element Analysis
4. XFEM Finite Element Analysis for Determining Crack Initiation, Crack Growth and Failure
5. FEA Examples

VII. ASME Section IX

1. Essential Variables, Non-Essential Variables, and Supplemental Variables
2. Welding Procedure Specification and Procedure Qualification Record
    a. Pre-Heat
    b. Maximum Interpass Temperature
    c. Post Weld Heat Treatment
    d. Weld Groove Dimensions
    e. Weave vs. Stringers
    f. Heat Input
    g. Welding Rod/Electrode Selection

VIII. National Board Inspection Code (NBIC) Alternative Welding Procedures

1. Welding Method 1
2. Welding Method 3 (Temper Bead Technique)

IX. Welding Metallurgical Aspects

1. Bake-Out (for Hydrogen Service to Prevent Cold Cracking)
2. Sensitization, Sigma Phase, Spheriodization, Graphitization, Grain Boundary Sulfur, Alpha Prime

Static Weld Designs

Figure 1: ASME Section VIII Div. 1 Weld Joint Type

Figure UW-3
Illustration of Welded Joint Locations Typical of Categories A, B, C, and D

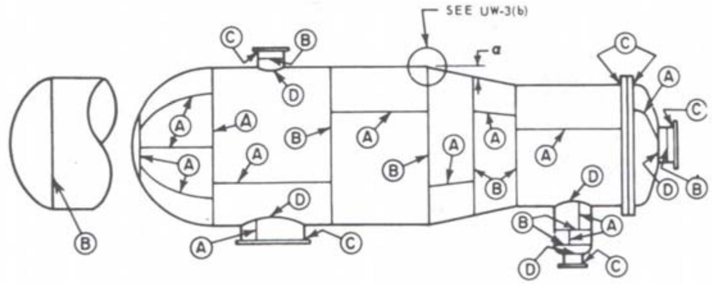


Figure 2: ASME Section VIII Div. 2 Weld Joint Type

Figure 4.2.1
Weld Joint Locations Typical of Categories A, B, C, D, and E

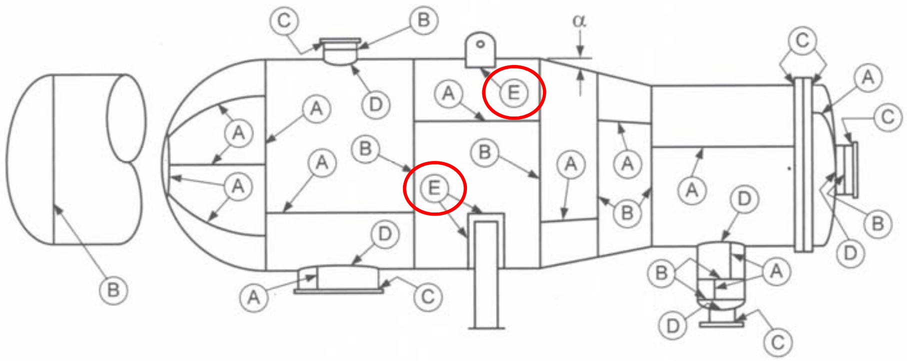


Figure 3: ASME Section VIII Div. 2 Weld Categories

Table 4.2.1
Definition of Weld Categories

Weld Category	Description
A	• Longitudinal and spiral welded joints within the main shell, communicating chambers [Note (1)], transitions in diameter, or nozzles • Any welded joint within a sphere, within a formed or flat head, or within the side plates [Note (2)] of a flat-sided vessel • Any butt-welded joint within a flat tubesheet • Circumferential welded joints connecting hemispherical heads to main shells, to transitions in diameter, to nozzles, or to communicating chambers
B	• Circumferential welded joints within the main shell, communicating chambers [Note (1)], nozzles or transitions in diameter including joints between the transition and a cylinder at either the large or small end • Circumferential welded joints connecting formed heads other than hemispherical to main shells, to transitions in diameter, to nozzles, or to communicating chambers
C	• Welded joints connecting flanges, Van Stone laps, tubesheets or flat heads to main shell, to formed heads, to transitions in diameter, to nozzles, or to communicating chambers [Note (1)] • Any welded joint connecting one side plate [Note (2)] to another side plate of a flat-sided vessel
D	• Welded joints connecting communicating chambers [Note (1)] or nozzles to main shells, to spheres, to transitions in diameter, to heads, or to flat-sided vessels • Welded joints connecting nozzles to communicating chambers [Note (1)] (for nozzles at the small end of a transition in diameter see Category B)
E	• Welded joints attaching nonpressure parts and stiffeners

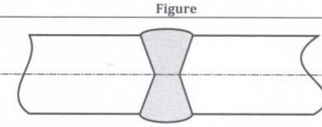
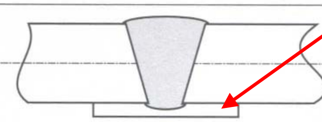
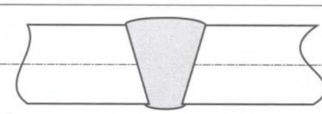
NOTES:
(1) Communicating chambers are defined as appurtenances to the vessel that intersect the shell or heads of a vessel and form an integral part of the pressure-containing enclosure, e.g., sumps.
(2) Side plates of a flat-sided vessel are defined as any of the flat plates forming an integral part of the pressure-containing enclosure.

Figure 4: ASME Section VIII Div. 2 Weld Types

Table 4.2.2
Definition of Weld Joint Types

Weld Joint Type	Description
1	Butt joints and angle joints where the cone half-apex angle is less than or equal to 30 deg produced by double welding or by other means which produce the same quality of deposited weld metal on both inside and outside weld surfaces. Welds using backing strips which remain in place do not qualify as Type No. 1 butt joints.
2	Butt joints produced by welding from one side with a backing strip that remains in place
3	Butt joints produced by welding from one side without a backing strip
7	Corner joints made with full penetration welds with or without cover fillet welds
8	Angle joints made with a full penetration weld where the cone half-apex angle is greater than 30 deg
9	Corner joints made with partial penetration welds with or without cover fillet welds
10	Fillet welds

Table 4.2.4
Some Acceptable Weld Joints for Shell Seams

Detail	Joint Type	Joint Category	Design Notes	Figure
1	1	A, B, C, D		
2	2	B		
3	3	B		

Backing Strip

Figure 5: ASME Section VIII Div. 1 Weld Joint Efficiencies

Table UW-12
Maximum Allowable Joint Efficiencies for Arc and Gas Welded Joints

Type No.	Joint Description	Limitations	Joint Category	Degree of Radiographic Examination (a) Full [Note (1)]	(b) Spot [Note (2)]	(c) None
(1)	Butt joints as attained by double-welding or by other means which will obtain the same quality of deposited weld metal on the inside and outside weld surfaces to agree with the requirements of UW-35. Welds using metal backing strips which remain in place are excluded.	None	A, B, C & D	1.00	0.85	0.70
(2)	Single-welded butt joint with backing strip other than those included under (1)	*(a)* None except as in (b) below	A, B, C & D	0.90	0.80	0.65
		*(b)*Circumferential butt joints with one plate offset; see UW-13(b)(4) and Figure UW-13.1, sketch (i)	A, B & C	0.90	0.80	0.65
(3)	Single-welded butt joint without use of backing strip	Circumferential butt joints only, not over 5/8 in. (16 mm) thick and not over 24 in. (600 mm) outside diameter	A, B & C	NA	NA	0.60
(4)	Double full fillet lap joint	*(a)* Longitudinal joints not over 3/8 in. (10 mm) thick	A	NA	NA	0.55
		(b) Circumferential joints not over 5/8 in. (16 mm) thick	B & C [Note (3)]	NA	NA	0.55
(5)	Single full fillet lap joints with plug welds conforming to UW-17	*(a)* Circumferential joints [Note (4)] for attachment of heads not over 24 in. (600 mm) outside diameter to shells not over 1/2 in. (13 mm) thick	B	NA	NA	0.50
		(b) Circumferential joints for the attachment to shells of jackets not over 5/8 in. (16 mm) in nominal thickness where the distance from the center of the plug weld to the edge of the plate is not less than 1 1/2 times the diameter of the hole for the plug.	C	NA	NA	0.50
(6)	Single full fillet lap joints without plug welds	*(a)* For the attachment of heads convex to pressure to shells not over 5/8 in. (16 mm) required thickness, only with use of fillet weld on inside of shell; or	A & B	NA	NA	0.45
		(b) for attachment of heads having pressure on either side, to shells not over 24 in. (600 mm) inside diameter and not over 1/4 in. (6 mm) required thickness with fillet weld on outside of head flange only	A & B	NA	NA	0.45
(7)	Corner joints, full penetration, partial penetration, and/or fillet welded	As limited by Figure UW-13.2 and Figure UW-16.1	C & D [Note (5)]	NA	NA	NA
(8)	Angle joints	Design per U-2(g) for Category B and C joints	B, C & D	NA	NA	NA

Note 5: There is no joint efficiency E in the design equations of this Division for Category C and D corner joints. When needed, a value of E not greater than 1.00 may be used.

Unless the sizing basis is given elsewhere in this Division, the allowable load on fillet welds shall equal the product of the weld area (based on minimum leg dimension), the allowable stress value in tension of the material being welded and E=0.55.

Figure 6: ASME Section VIII Div. 2 Weld Joint Efficiencies

ISO 15608

1.1 Carbon Steel
1.2 High Strength CS

8.1 Austenitic SS

9.1, 9.2, 9.3 Nickel Alloys

10 Duplex SS

Table 7.2
Nondestructive Examination

Joint Category	Type of Weld (see Table 4.2.2)			Type of NDE [Note (1)]	1a	1b	2a	2b	3a	3b
	Examination Group				1a	1b	2a	2b	3a	3b
	Permitted Materials				All Materials in Annex 3-A	Groups 1.1, 1.2, 8.1	Groups 8.2, 9.1, 9.2, 9.3, 10	Groups 1.1, 1.2, 8.1	Groups 8.2, 9.1, 9.2, 10	Groups 1.1, 1.2, 8.1
	Weld Joint Efficiency				1.0	1.0	1.0	1.0	0.85	0.85
					Extent of NDE [Note (2)] [Note (3)]					
A	Full penetration butt weld (see Table 4.2.4 and Table 4.2.5)	1	Longitudinal joints	RT or UT	100%	100%	100%	100%	25%	10%
				MT or PT	10%	10% [Note (4)]	10%	0	0	0
B		1	Circumferential joints on a shell, including circumferential joints between a shell and a non-hemispherical head	RT or UT	25%	10%	25%	10%	10%	5% [Note (5)]
				MT or PT	10%	10% [Note (4)]	10%	0	0	0
B		2, 3	Circumferential joints on a shell, including circumferential joints between a shell and a non-hemispherical head, with backing strip (as limited by 4.2.5.3)	RT	NP	100%	NP	25%	NP	25%
				MT or PT	NP	10%	NP	10%	NP	10%
B		1	Circumferential joints on a nozzle where d > 150 mm (6 in.) and t_n > 16 mm (5/8 in.)	RT or UT	25%	10%	25%	10%	10%	5% [Note (5)]
				MT or PT	10%	10% [Note (4)]	10%	10% [Note (4)]	10%	10% [Note (4)]
B		2, 3	Circumferential joints on a nozzle where d > 150 mm (6 in.) and t_n > 16 mm (5/8 in.) with backing strip (as limited by 4.2.5.3)	RT	NP	100%	NP	100%	NA	25%
				MT or PT	NP	10%	NP	10%	100%	10%
B		1	Circumferential joints on a nozzle where d ≤ 150 mm (6 in.) or t_n ≤ 16 mm (5/8 in.)	RT or UT	NA	NA	NA	NA	NA	NA
				MT or PT	25%	10%	25%	10%	10%	5%
A		1	All welds in spheres, heads, and hemispherical heads to shells	RT or UT	100%	100%	100%	100%.	25%	10%
				MT or PT	10%	10% [Note (4)]	10%	0	0	0
A		1	All butt welds in flat tubesheets	RT or UT	100%	100%	100%	100%	100%	100%
B		1	Attachment of a conical shell with a cylindrical shell without a knuckle (large end of the cone) [Note (6)] [Note (7)]	RT or UT	100%	25%	100%	25%	10%	10%
				MT or PT	100%	100%	100%	100%	100%	100%

ASME Section VIII Div. 1 Internal Pressure Formula

<u>Circumferential Stress (Longitudinal Joints)</u>

$$t = \frac{PR}{SE - 0.6P} \text{ or } P = \frac{SEt}{R + 0.6t}$$

<u>Longitudinal Stress (Circumferential Joints)</u>

$$t = \frac{PR}{2SE + 0.4P} \text{ or } P = \frac{2SEt}{R - 0.4t}$$

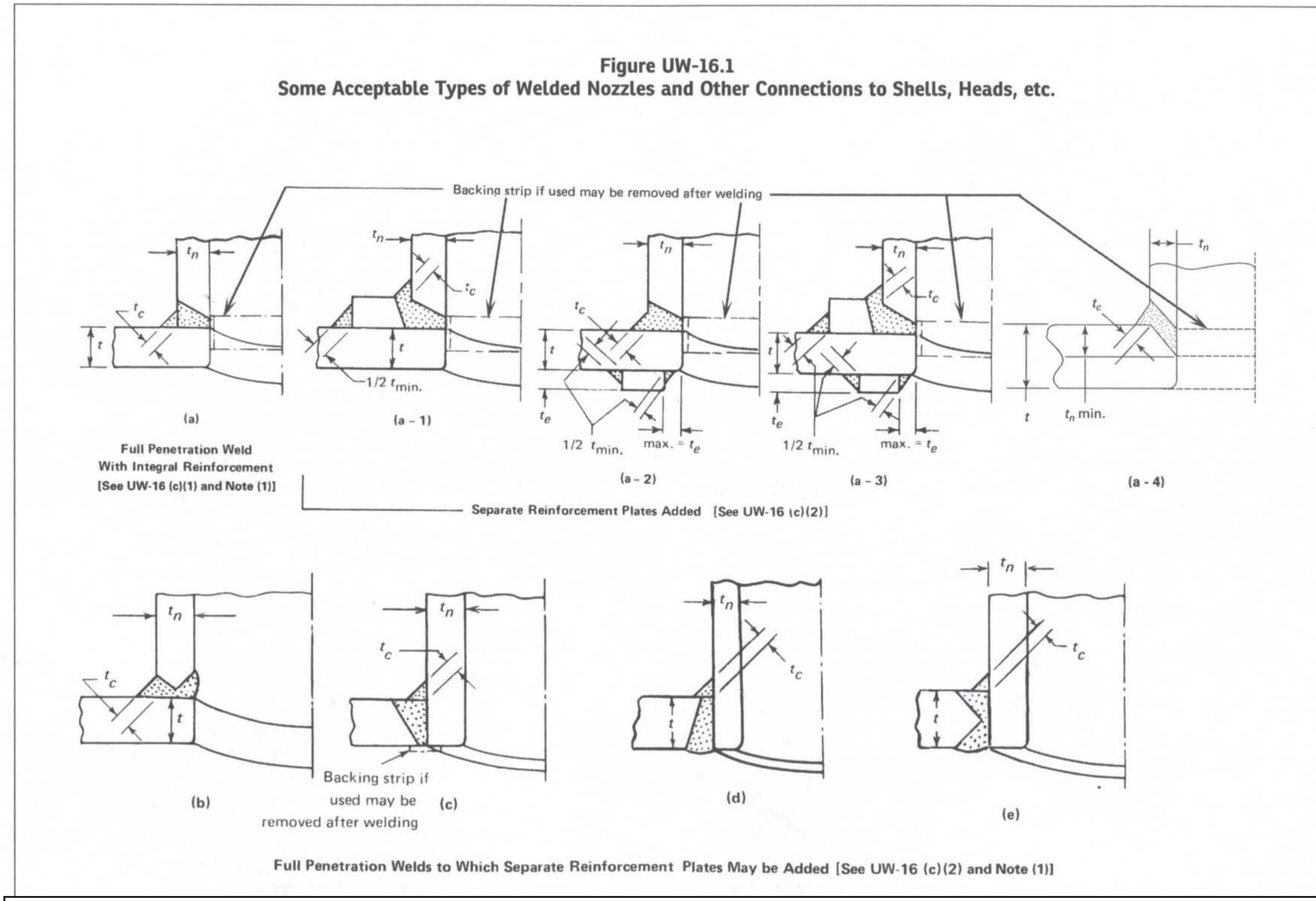
ASME Section VIII Div. 2 Internal Pressure Design by Formula

<u>Cylindrical Shells</u>

$$t = \frac{D}{2}\left(exp\left[\frac{P}{SE}\right] - 1\right)$$

R and D are based on ID.
S (SA-516 70) = 20-ksi (Safety Factor of 3.5 on UTS)
Sm (SA-516 70) = 23,300-ksi (Safety Factor of 3.0 on UTS)

Figure 7: ASME Section VIII Div. 1 and VIII Div. 2 Part 4 (DBF) – Pre-Approved Weld Designs



tmin = the smaller of ¾” or the thickness of the thinner of the parts joined by a fillet, single-bevel, or single-J weld.

tc = not less than the smaller of ¼” or 0.7tmin.

ASME Section VIII – Div. 2 Part 5 – 5.2.2 Elastic Stress Analysis Method

5.2.2.1 Overview ...A quantity known as the equivalent stress is computed at locations in the component and compared to an allowable value of equivalent stress to determine if the component is suitable for the intended design conditions.

$$S_e = \sigma_e = \frac{1}{\sqrt{2}}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{0.5}$$

A finite element analysis (FEA) model is created to generate stress plots for the following load cases, as applicable. Don't use Elastic Stress Analysis method for heavy walls (R/t ⩾4).

Figure 8: Div. 2 Load Cases for Elastic Analysis

Table 5.3
Load Case Combinations and Allowable Stresses for an Elastic Analysis

	Design Load Combination [Note (1)]	Allowable Stress
(1)	$P + P_s + D$	Determined based on the Stress Category shown in Figure 5.1
(2)	$P + P_s + D + L$	
(3)	$P + P_s + D + L + T$	
(4)	$P + P_s + D + S_s$	
(5)	$0.6D + (0.6W \text{ or } 0.7E)$ [Note (2)]	
(6)	$0.9P + P_s + D + (0.6W \text{ or } 0.7E)$	
(7)	$0.9P + P_s + D + 0.75(L + T) + 0.75S_s$	
(8)	$0.9P + P_s + D + 0.75(0.6W \text{ or } 0.7E) + 0.75L + 0.75S_s$	
(9)	$P_T + P_s + D + 0.6W_{pt}$	See 5.2.2.5

GENERAL NOTE: Loads listed herein shall be considered to act in the combinations described above; whichever produces the most unfavorable effect in the component being considered. Effects of one or more loads not acting shall be considered.

NOTES:
(1) The parameters used in the Design Load Combination column are defined in Table 5.2.
(2) This load combination addresses an overturning condition for foundation design. It does not apply to design of anchorage (if any) to the foundation. Refer to ASCE/SEI 7-10, 2.4.1 Exception 2 for an additional reduction to W that may be applicable.

Figure 9: Stress Classification Line

Figure 5-A.1
Stress Classification Line (SCL) and Stress Classification Plane (SCP)

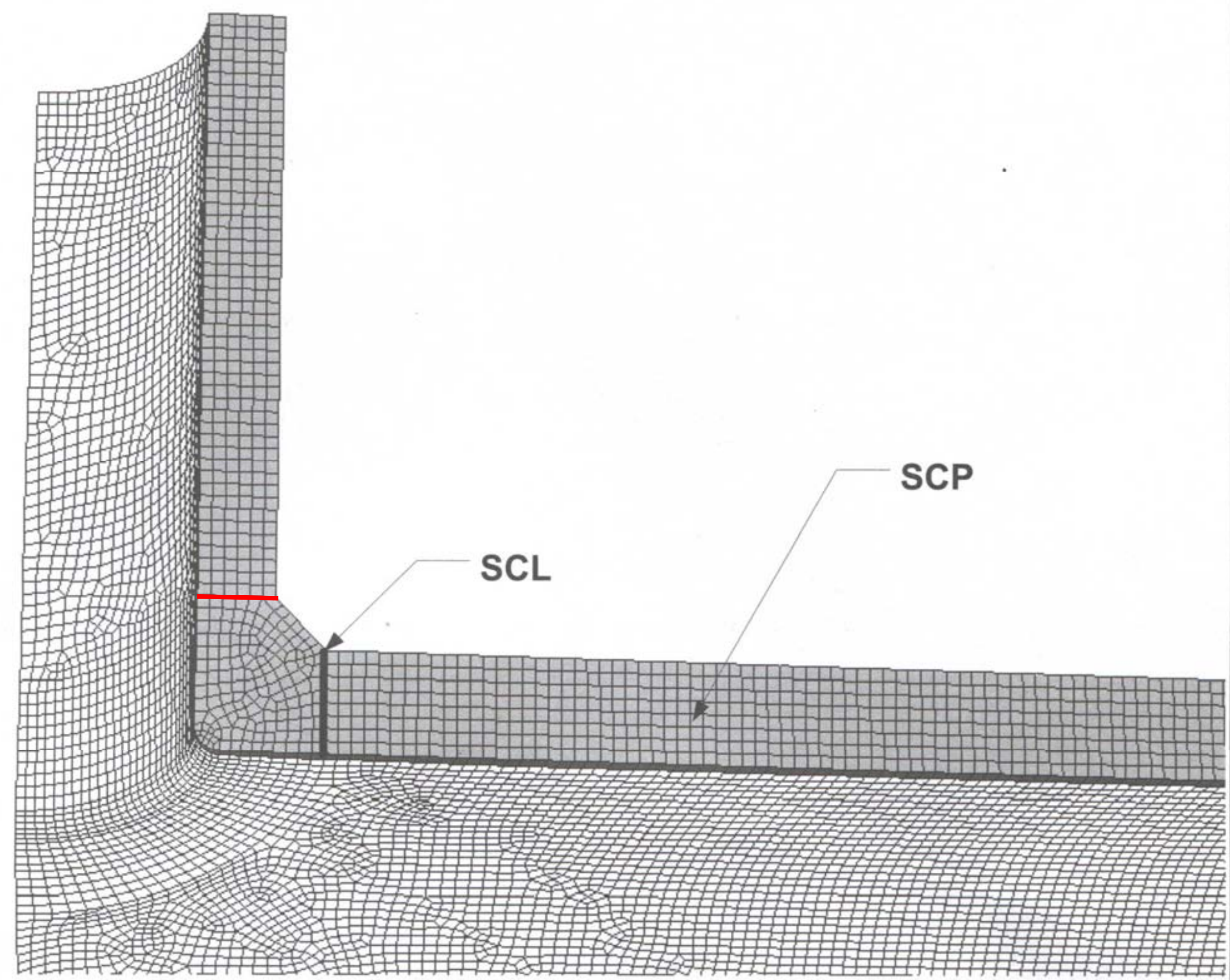


Figure 10: Pm, Pb, Q, F

Figure 5-A.4

Computation of Membrane and Bending Equivalent Stresses by the Stress Integration Method Using the Results From a Finite Element Model With Continuum Elements

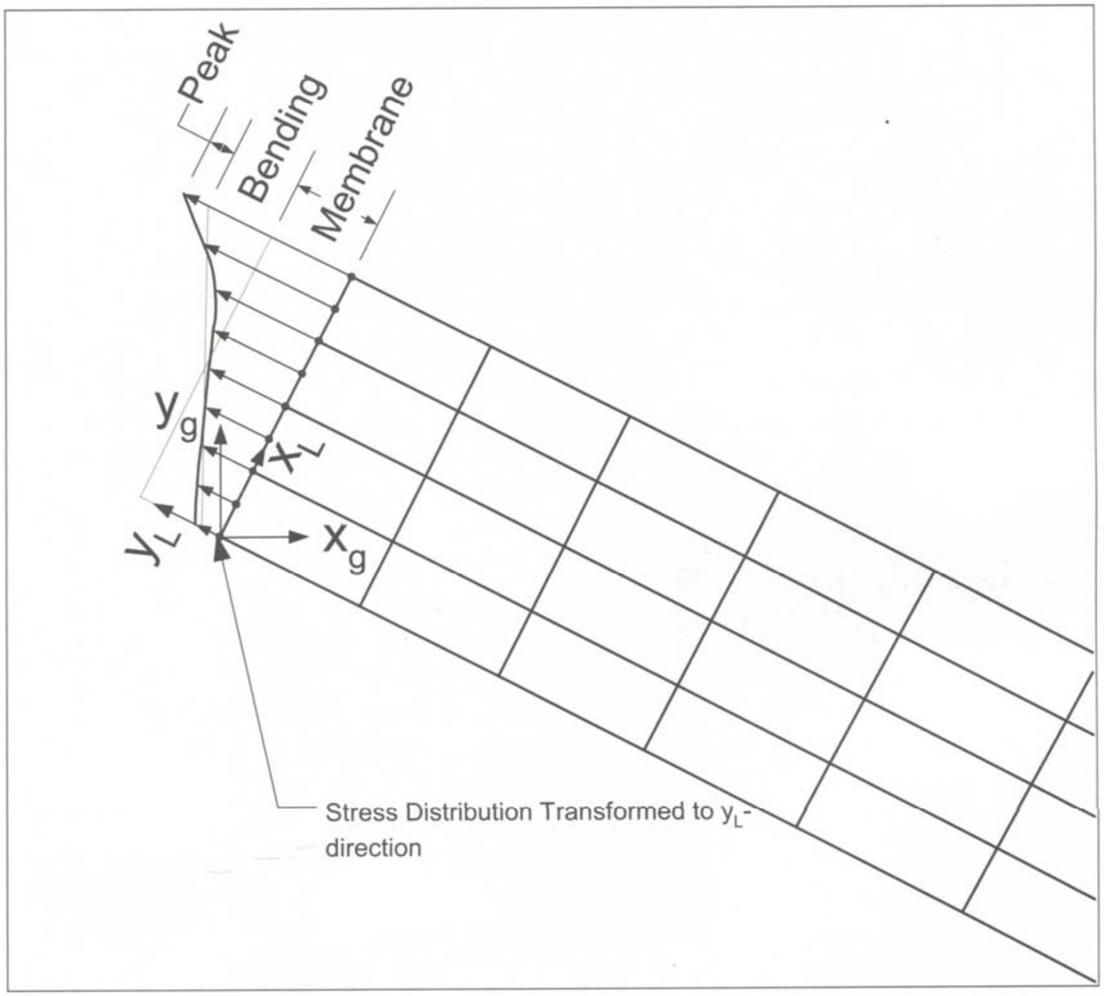


Figure 11A: Examples of Stress Classification – 1

Table 5.6
Examples of Stress Classification

Vessel Component	Location	Origin of Stress	Type of Stress	Classification
Any shell including cylinders, cones, spheres, and formed heads	Shell plate remote from discontinuities	Internal pressure	General membrane	P_m
			Gradient through plate thickness	Q
		Axial thermal gradient	Membrane	Q
			Bending	
	Near nozzle or other opening	Net-section axial force and/ or bending moment applied to the nozzle, and/ or internal pressure	Local membrane	P_L
			Bending	Q
			Peak (fillet or corner)	F
	Any location	Temperature difference between shell and head	Membrane	Q
			Bending	
	Shell distortions such as out-of-roundness and dents	Internal pressure	Membrane	P_m
			Bending	Q
Cylindrical or conical shell	Any section across entire vessel	Net-section axial force, bending moment applied to the cylinder or cone, and/or internal pressure	Membrane stress averaged through the thickness, remote from discontinuities; stress component perpendicular to cross section	P_m
			Bending stress through the thickness; stress component perpendicular to cross section	P_b
	Junction with head or flange	Internal pressure	Membrane	P_L
			Bending	Q
Dished head or conical head	Crown	Internal pressure	Membrane	P_m
			Bending	P_b
	Knuckle or junction to shell	Internal pressure	Membrane	P_L [Note (1)]
			Bending	Q
Flat head	Center region	Internal pressure	Membrane	P_m
			Bending	P_b
	Junction to shell	Internal pressure	Membrane	P_L
			Bending	Q [Note (2)]
Perforated head or shell	Typical ligament in a uniform pattern	Pressure	Membrane (averaged through cross section)	P_m
			Bending (averaged through width of ligament., but gradient through plate)	P_b
			Peak	F
	Isolated or atypical ligament	Pressure	Membrane	Q
			Bending	F
			Peak	

Figure 11B: Examples of Stress Classification – 2

Table 5.6
Examples of Stress Classification (Cont'd)

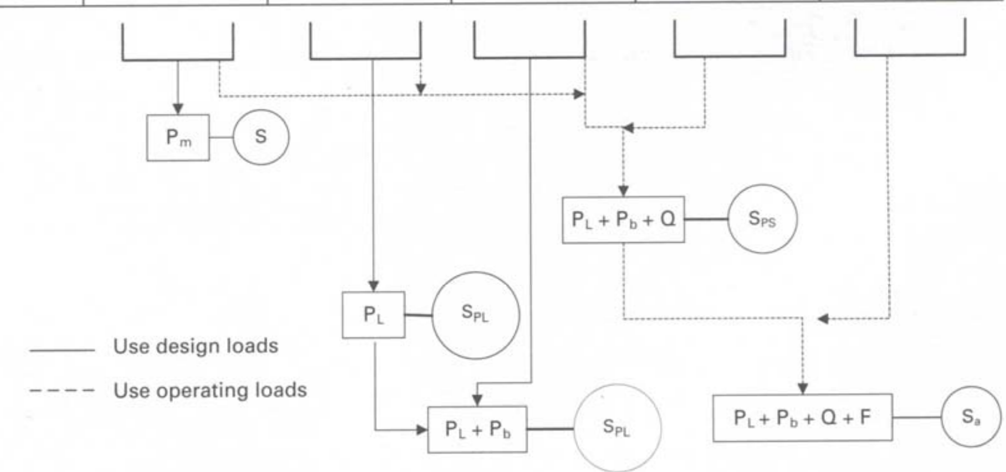
Vessel Component	Location	Origin of Stress	Type of Stress	Classification
Nozzle (see 5.6)	Within the limits of reinforcement given by 4.5	Pressure and external loads and moments, including those attributable to restrained free end displacements of attached piping	General membrane	P_m
			Bending (other than gross structural discontinuity stresses) averaged through nozzle thickness	
	Outside the limits of reinforcement given by 4.5	Pressure and external axial, shear, and torsional loads, including those attributable to restrained free end displacements of attached piping	General membrane	P_m
		Pressure and external loads and moments, excluding those attributable to restrained free end displacements of attached piping	Membrane	P_L
			Bending	P_b
		Pressure and all external loads and moments	Membrane	P_L
			Bending	Q
			Peak	F
	Nozzle wall	Gross structural discontinuities	Membrane	P_L
			Bending	Q
			Peak	F
		Differential expansion	Membrane	Q
			Bending	
			Peak	F
Cladding	Any	Differential expansion	Membrane	F
			Bending	
Any	Any	Radial temperature distribution [Note (3)]	Equivalent linear stress [Note (4)]	Q
			Nonlinear portion of stress distribution	F
Any	Any	Any	Stress concentration (notch effect)	F

NOTES:
(1) Consideration shall be given to the possibility of wrinkling and excessive deformation in vessels with large diameter-to-thickness ratio.
(2) If the bending moment at the edge is required to maintain the bending stress in the center region within acceptable limits, the edge bending is classified as P_b; otherwise, it is classified as Q.
(3) Consider possibility of thermal stress ratchet.
(4) Equivalent linear stress is defined as the linear stress distribution that has the same net bending moment as the actual stress distribution.

Figure 12: Stress Category Hopper

Figure 5.1
Stress Categories and Limits of Equivalent Stress

Stress Category	Primary: General Membrane	Primary: Local Membrane	Primary: Bending	Secondary Membrane plus Bending	Peak
Description (For examples, see Table 5.2)	Average primary stress across solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads.	Average stress across any solid section. Considers discontinuities but not concentrations. Produced only by mechanical loads.	Component of primary stress proportional to distance from centroid of solid section. Excludes discontinuities and concentrations. Produced only by mechanical loads.	Self-equilibrating stress necessary to satisfy continuity of structure. Occurs at structural discontinuities. Can be caused by mechanical load or by differential thermal expansion. Excludes local stress concentrations.	1. Increment added to primary or secondary stress by a concentration (notch). 2. Certain thermal stresses which may cause fatigue but not distortion of vessel shape.
Symbol	P_m	P_L	P_b	Q	F

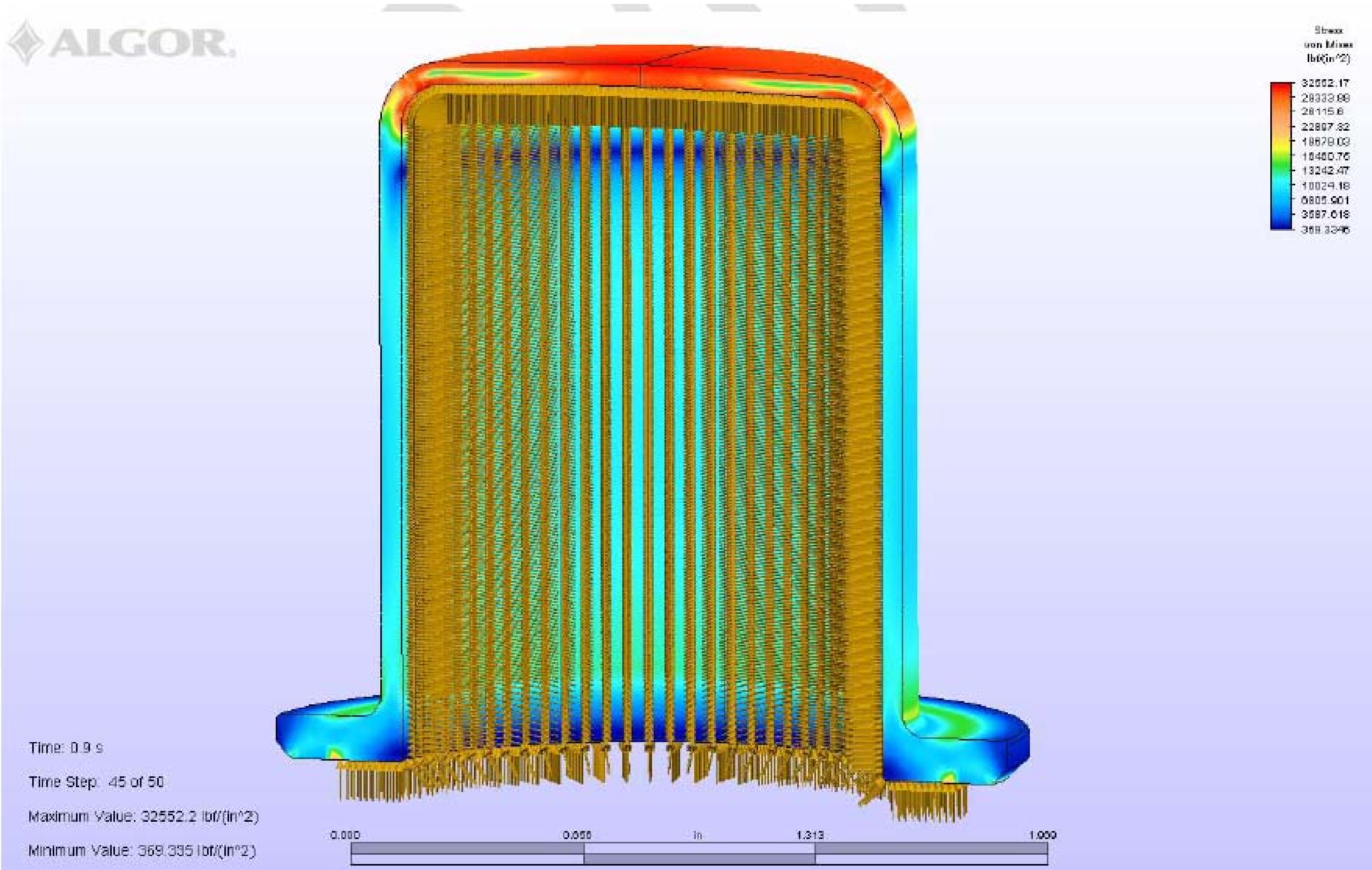


$S = S_m$ (II Part D)

S_{PL} = greater of 1.5S or Sy

Sps = greater of 3S or 2Sy (taken at average temperature of cycle.

Example FEA Model and Evaluation for Elastic Stress Method
(External PDF Containment_10May10)



ASME Section VIII – Div. 2 Part 5 – 5.2.3 Limit-Load Analysis Method

1. The material model is elastic-perfectly plastic with a specified yield strength.
2. Use small displacement theory for FEA.
3. Loss of equilibrium defines limit point (either due to gross yielding, or local/gross buckling).
4. Very simple to use. Setup model, apply materials, loads, and constraints, and test for convergence at design partial safety factors. No SCL or stress categorization required. Mesh insensitive.
5. Strain results are unusable. Must use E-P Analysis for local damage check.

Class Designation

1. **Class 1 –** Design follows Part 4 DBF and Part 5 DBA is only used where design rules in Part 4 are not provided for a particular part design. Class 1 DBA shall not be used in lieu of DBF Part 4 Rules.
2. **Class 2 –** The entire design is per Part 5 DBA rules.

Figure 13: Load Factor β and Pressure Test Factor β_T

Table 4.1.3
Load Factor, β, and Pressure Test Factors, β_T, γ_{min}, and $\gamma_{St/S}$, for Class 1 and Class 2 Construction and Hydrostatic or Pneumatic Testing

Class	β	β_T Hydrostatic	β_T Pneumatic	γ_{min} Hydrostatic	γ_{min} Pneumatic	$\gamma_{St/S}$ Hydrostatic	$\gamma_{St/S}$ Pneumatic
1	3.0	0.95	0.8	$1.5\beta_T$	$1.5\beta_T$	1.25	1.15
2	2.4	0.95	0.8	$1.5\beta_T$	$1.5\beta_T$	1.25	1.15

Figure 14: Div. 2 Load Cases for Limit Load Analysis

Table 5.4
Load Case Combinations and Load Factors for a Limit-Load Analysis

Criteria	Required Factored Load Combinations
	Design Conditions
Global	(1) $1.5(P + P_s + D)$
	(2) $1.3(P + P_s + D + T) + 1.7L + 0.54S_s$
	(3) $1.3(P + P_s + D) + 1.7S_s + (1.1L \text{ or } 0.54W)$
	(4) $1.3(P + P_s + D) + 1.1W + 1.1L + 0.54S_s$
	(5) $1.3(P + P_s + D) + 1.1E + 1.1L + 0.21S_s$
Local	See 5.3.1.2
Serviceability	Per User's Design Specification, if applicable; see Table 5.5
	Test Condition
Global	$\frac{1}{\beta_T}\left(P_T + P_S + D + 0.6W_{pt}\right)$
Serviceability	Per User's Design Specification, if applicable

GENERAL NOTES:
(a) The parameters used in the Design Load Combination column are defined in Table 5.2.
(b) See 5.2.3.4 for descriptions of global and serviceability criteria.
(c) S is the allowable membrane stress at the design temperature.
(d) S_T is the allowable membrane stress at the pressure test temperature.
(e) Loads listed herein shall be considered to act in the combinations described above; whichever produces the most unfavorable effect in the component being considered. Effects of one or more loads not acting shall be considered.

Table 5.5
Load Case Combinations and Load Factors for an Elastic–Plastic Analysis

Criteria	Required Factored Load Combinations
	Design Conditions
Global	(1) $\beta(P + P_s + D)$
	(2) $0.88\beta(P + P_S + D + T) + 1.13\beta L + 0.36\beta S_S$
	(3) $0.88\beta(P + P_S + D) + 1.13\beta S_s + 0.71\beta W$ or $0.36\beta W$
	(4) $0.88\beta(P + P_S + D) + 0.71\beta W + 0.71\beta L + 0.36\beta S_S$
	(5) $0.88\beta(P + P_S + D) + 0.71\beta E + 0.71\beta L + 0.14\beta S_S$
Local	$1.7(P + P_s + D)$
Serviceability	Per User's Design Specification, if applicable; see 5.2.4.3(b)
	Test Condition
Global	$\frac{\beta}{1.5} \times \frac{1}{\beta_T}\left(P_T + P_S + D + 0.6W_{pt}\right)$
Serviceability	Per User's Design Specification, if applicable

GENERAL NOTES:
(a) The parameters used in the Design Load Combination column are defined in Table 5.2.
(b) See 5.2.4.3 for descriptions of global and serviceability criteria.
(c) S is the allowable membrane stress at the design temperature.
(d) S_T is the allowable membrane stress at the pressure test temperature.
(e) Loads listed herein shall be considered to act in the combinations described above; whichever produces the most unfavorable effect in the component being considered. Effects of one or more loads not acting shall be considered.

ASME Section VIII – Div. 2 Part 5 – 5.2.4 Elastic-Plastic Stress Analysis Method

1. The material model is elastic-plastic (full stress-strain curve); however, use of elastic-perfectly plastic material model is acceptable (is conservative).

2. Use large displacement theory for FEA.

3. Loss of equilibrium defines failure (either due to ultimate failure, or local/gross buckling).
4. More data than Limit Load method is required. Setup model, apply materials, loads, and constraints, and test for convergence at design partial safety factors. No SCL or stress categorization required. This method is mesh sensitive, but is the most accurate. Provide mesh sensitivity study and/or perform submodeling of areas of interest.
5. ASME Section VIII Div. 2 Annex 3-D 3-D.3 Stress Strain Curve provides the equation and data necessary to estimate full stress-strain curves for materials.

Figure 15: Div. 2 Load Cases for Elastic-Plastic Analysis

Table 5.5
Load Case Combinations and Load Factors for an Elastic–Plastic Analysis

Criteria	Required Factored Load Combinations
	Design Conditions
Global	(1) $\beta(P + P_S + D)$ (2) $0.88\beta(P + P_S + D + T) + 1.13\beta L + 0.36\beta S_S$ (3) $0.88\beta(P + P_S + D) + 1.13\beta S_s + 0.71\beta W$ or $0.36\beta W$ (4) $0.88\beta(P + P_S + D) + 0.71\beta W + 0.71\beta L + 0.36\beta S_S$ (5) $0.88\beta(P + P_S + D) + 0.71\beta E + 0.71\beta L + 0.14\beta S_S$
Local	$1.7(P + P_S + D)$
Serviceability	Per User's Design Specification, if applicable; see 5.2.4.3(b)
	Test Condition
Global	$\frac{\beta}{1.5} \times \frac{1}{\beta_T}\left(P_T + P_S + D + 0.6W_{pt}\right)$
Serviceability	Per User's Design Specification, if applicable

GENERAL NOTES:

(a) The parameters used in the Design Load Combination column are defined in Table 5.2.

(b) See 5.2.4.3 for descriptions of global and serviceability criteria.

(c) S is the allowable membrane stress at the design temperature.

(d) S_T is the allowable membrane stress at the pressure test temperature.

(e) Loads listed herein shall be considered to act in the combinations described above; whichever produces the most unfavorable effect in the component being considered. Effects of one or more loads not acting shall be considered.

Example FEA Model and Evaluation for Limit Load and Elastic-Plastic Analysis Methods (External PDF Containment_10May10)

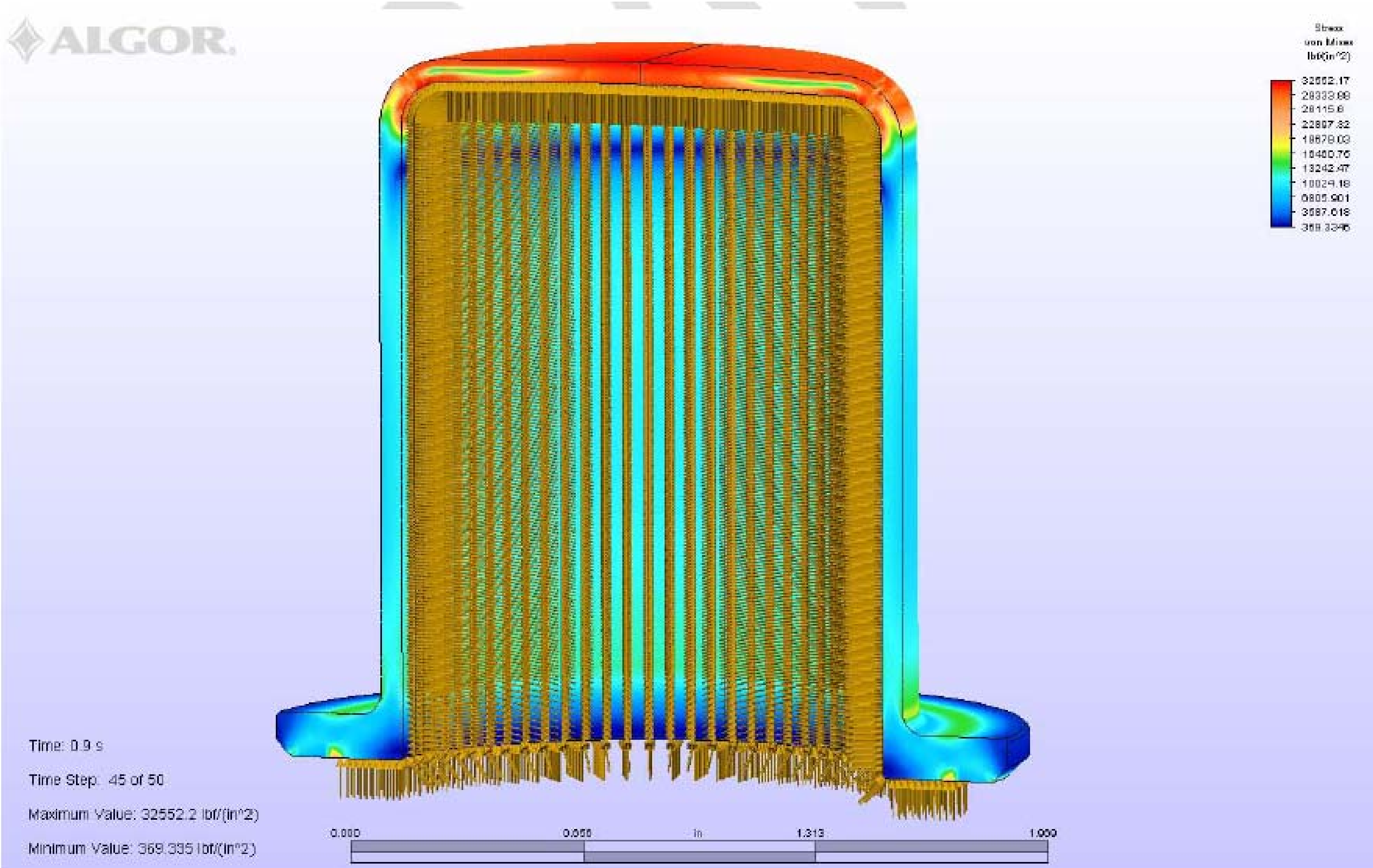


Figure 16: Limit Load Additional Example

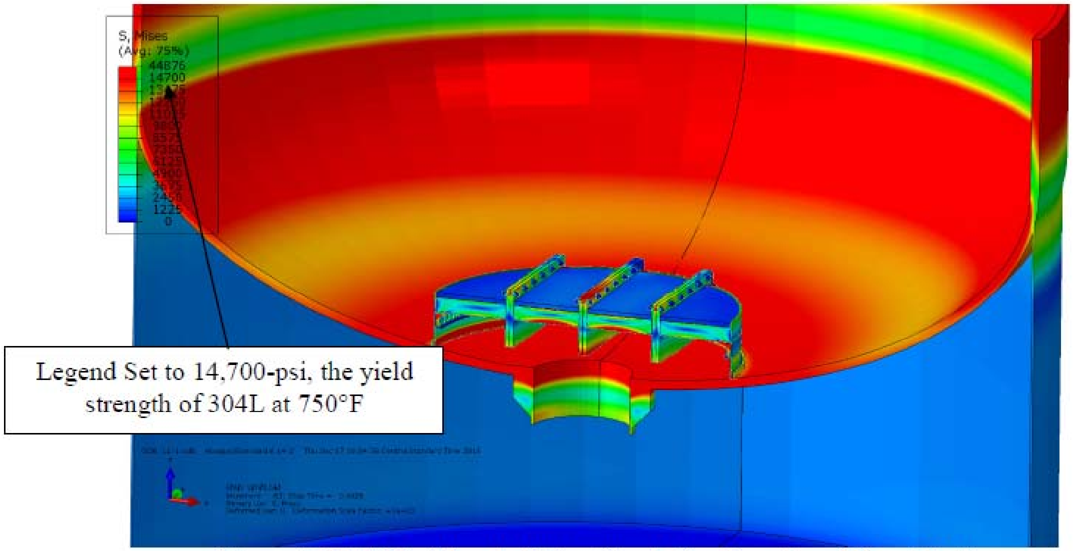


Figure 6: FEA Limit Load at Time Step 1.60 – Overview of Vessel Bottom

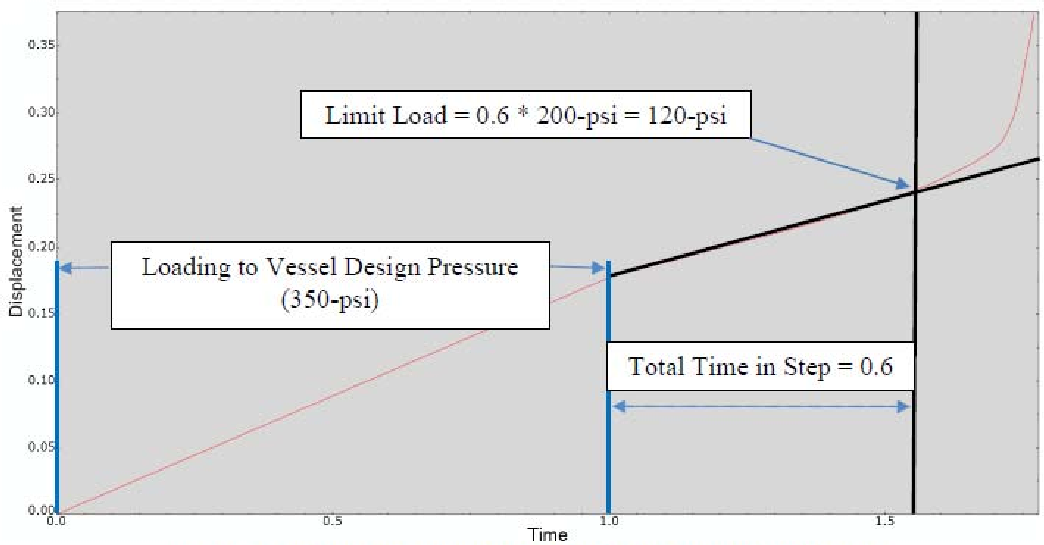


Figure 7: FEA Limit Load based on Gross Yielding Displacement

ASME Section VIII – Div. 2 Part 5 – 5.3 Protection Against Local Failure

1. This check not required if the design is proven by Part 4 DBF.
2. Two methods to perform:

5.3.2 Elastic Analysis – Triaxial Stress Limit. The algebraic sum of the three linearized primary principal stresses from Design Load Combination (1) of Table 5.3 shall be used for checking this criterion.

$$(\sigma_1 + \sigma_2 + \sigma_3) \leq 4S$$

5.3.3 Elastic-Plastic Analysis – Local Strain Limit. Perform an elastic-plastic stress analysis based on the load case combinations for the local criteria given in Table 5.5. The effects of non-linear geometry shall be considered in the analysis.

Protection Against Local Failure – FEA Example

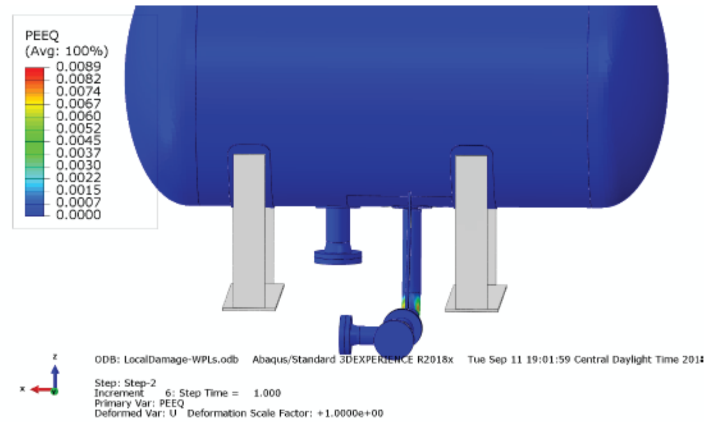


Figure 16: Local Failure Model – Plastic Strains

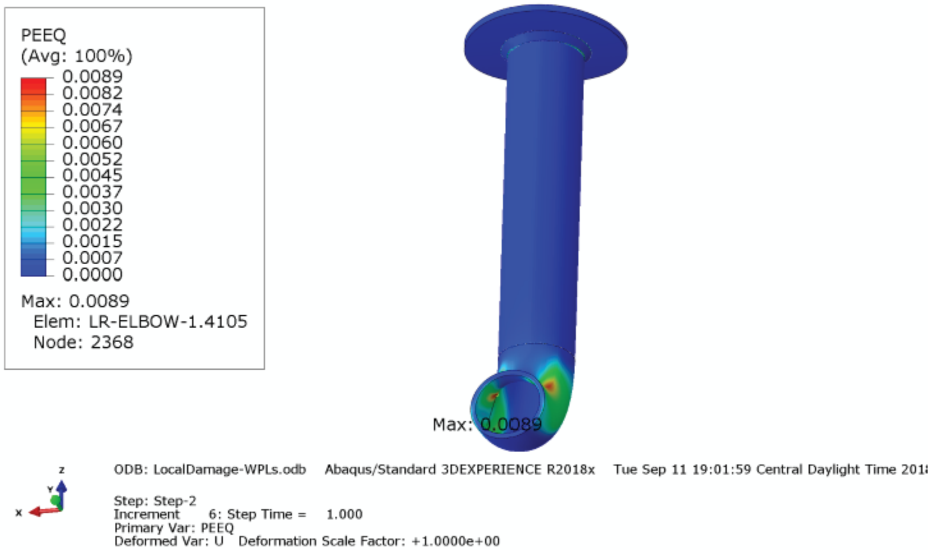


Figure 17: Local Failure Model – Plastic Strains – Large Radius Elbow

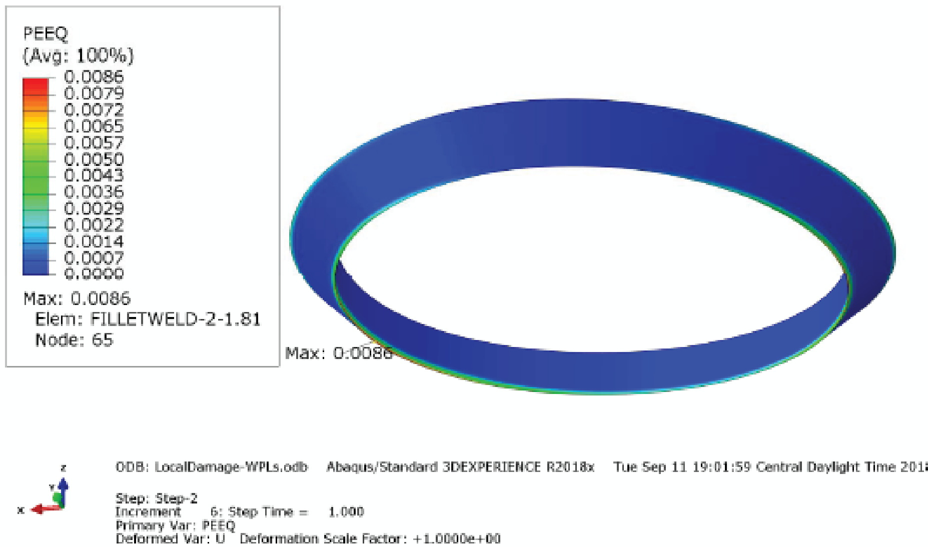


Figure 18: Local Failure Model – Plastic Strains – Nozzle G1 Outer Fillet Weld

Per ASME Section VIII Div. 2, for each point in the component being evaluated, determine the three principal stresses (σ_1, σ_2, and σ_3), the equivalent stress (von Mises Stress Intensity, σ_e), and the equivalent strain (PEEQ).

Table 5: Local Failure Data

	LR Elbow (Node 2368)	Nozzle G1 Fillet Weld (Node 65)
σ_1	28164	-8879
σ_2	12802	-19756
σ_3	-454	-38406
σ_e	24807	25865
ε_{peeq}	0.0089	0.0086

Determine the limiting triaxial strain, ε_L, using Eq. 5.6 below (with ε_{Lu}, m_2, and α_{sl} defined in Table 5.7).

$$\varepsilon_L = \varepsilon_{Lu} exp\left[-\left(\frac{\alpha_{sl}}{1+m_2}\right) * \left(\frac{\sigma_1+\sigma_2+\sigma_3}{3\sigma_e}\right) - \frac{1}{3}\right]$$

Where,

R = ratio of the min specified YS divided by the min specified UTS = 25-ksi/70-ksi = 0.357
m_2 = 0.75 (1.00-R) = 0.75 (1.00 – 0.357) = 0.482 for 304L
α_{sl} = 0.6 for 304L
ε_{Lu} = m_2 = 0.482 for elongation and reduction of area not specified for weld material.

LR Elbow:

$$\varepsilon_L = (0.482)exp\left[-\left(\frac{0.5}{1+0.482}\right)*\left(\frac{28164+12802-454}{3(24807)}\right)-\frac{1}{3}\right] = 0.287$$

Nozzle G1 Fillet Weld

$$\varepsilon_L = (0.482)exp\left[-\left(\frac{0.5}{1+0.482}\right)*\left(\frac{-8879-19756-38406}{3(25865)}\right)-\frac{1}{3}\right] = 0.462$$

Most forming strains typically do not exceed 5% (0.05); thus, ε_{cf} is assumed to be 0.05.

Criteria Check

Determine if the strain limit is satisfied (Eq. 5.7).

$$\varepsilon_{peeq} + \varepsilon_{cf} \leqslant \varepsilon_L$$

Table 6: Local Strain Limit Check

	LR Elbow (Node 2368)	**Nozzle G1 Fillet Weld (Node 7900)**
Limit	**0.287**	**0.462**
Actual	**0.0089+0.050 = 0.0589**	**0.0086+0.050 = 0.0586**

Both actual strains are well less than their limiting strain. The fillet weld limiting strain is much higher than the limit for the LR elbow because the fillet weld strain is completely compressive.

Cyclic (Fatigue) Weld Designs

Screening Criteria for Fatigue Analysis – Section 5.5.2 of Div. 2 Code provides two screening method for determining if a cyclic analysis is required.

ASME Section VIII Div. 2 5.5.3 Fatigue Assessment – Elastic Stress Analysis and Equivalent Stresses

Stress tensor is taken directly from the FEA plot (σ_{11}, σ_{22}, σ_{33}, σ_{12}, σ_{23}, σ_{31}), at areas of expected highest PL+Pb+Q+F fluctuations. Multiple locations may need to be evaluated. Multiple cycle ranges (k^{th}) may need to be evaluated. Two models will be needed, one with all loads, and one with only thermal loads (Local Thermal – LT). Cycle is between times "n" and "m".

Step 1: Determine stress tensor range minus thermal loads.

$$\Delta\sigma_{ij,k} = \left(\sigma_{ij,k} - \sigma_{ij,k}^{LT}\right)_m - \left(\sigma_{ij,k} - \sigma_{ij,k}^{LT}\right)_n$$

Step 2: Calculate intensity stress range of PL+Pb+Q+F minus thermal loads.

$$\left(\Delta S_{p,k} - \Delta S_{LT,k}\right) = \frac{1}{\sqrt{2}}\left[\left(\Delta\sigma_{11,k} - \Delta\sigma_{22,k}\right)^2 + \left(\Delta\sigma_{11,k} - \Delta\sigma_{33,k}\right)^2 + \left(\Delta\sigma_{22,k} - \Delta\sigma_{33,k}\right)^2 + 6\left(\Delta\sigma_{12,k}^2 + \Delta\sigma_{13,k}^2 + \Delta\sigma_{23,k}^2\right)\right]^{0.5}$$

Step 3: Determine stress tensor range for only thermal loads.

$$\Delta\sigma_{ij,k}{}^{LT} = \left(\sigma_{ij,k}^{LT}\right)_m - \left(\sigma_{ij,k}^{LT}\right)_n$$

Step 4: Calculate stress intensity range of PL+Q+F for thermal loads only (no Pb).

$$\Delta S_{LT,k} = \frac{1}{\sqrt{2}}\left[\left(\Delta\sigma_{11,k}^{LT} - \Delta\sigma_{22,k}^{LT}\right)^2 + \left(\Delta\sigma_{11,k}^{LT} - \Delta\sigma_{22,k}^{LT}\right)^2 + \left(\Delta\sigma_{22,k}^{LT} - \Delta\sigma_{33,k}^{LT}\right)^2\right]^{0.5}$$

Step 5: Determine the effective alternating equivalent stress amplitude for the kth cycle.

$$S_{alt,k} = \frac{K_f K_{e,k}(\Delta S_{p,k} - \Delta S_{LT,k}) + K_{v,k}\Delta S_{LT,k}}{2}$$

K_f (fatigue strength reduction factor) is taken in Div. 2 Tables 5.11 and 5.12.

Figure 17: Weld Surface Fatigue-Strength-Reduction Factors (Table 5.11)

Table 5.11
Weld Surface Fatigue-Strength-Reduction Factors

Weld Condition	Surface Condition	Quality Levels (See Table 5.12) 1	2	3	4	5	6	7
Full penetration	Machined	1.0	1.5	1.5	2.0	2.5	3.0	4.0
	As-welded	1.2	1.6	1.7	2.0	2.5	3.0	4.0
Partial penetration	Final surface machined	NA	1.5	1.5	2.0	2.5	3.0	4.0
	Final surface as-welded	NA	1.6	1.7	2.0	2.5	3.0	4.0
	Root	NA	NA	NA	NA	NA	NA	4.0
Fillet	Toe machined	NA	NA	1.5	NA	2.5	3.0	4.0
	Toe as-welded	NA	NA	1.7	NA	2.5	3.0	4.0
	Root	NA	NA	NA	NA	NA	NA	4.0

Figure 18: Weld Surface Fatigue-Strength-Reduction Factors (Table 5.12)

Table 5.12
Weld Surface Fatigue-Strength-Reduction Factors

Fatigue-Strength-Reduction Factor	Quality Level	Definition
1.0	1	Machined or ground weld that receives a full volumetric examination, and a surface that receives MT/PT examination and a VT examination
1.2	1	As-welded weld that receives a full volumetric examination, and a surface that receives MT/PT and VT examination
1.5	2	Machined or ground weld that receives a partial volumetric examination, and a surface that receives MT/PT examination and VT examination
1.6	2	As-welded weld that receives a partial volumetric examination, and a surface that receives MT/PT and VT examination

Table 5.12
Weld Surface Fatigue-Strength-Reduction Factors (Cont'd)

Fatigue-Strength-Reduction Factor	Quality Level	Definition
1.5	3	Machined or ground weld surface that receives MT/PT examination and a VT examination (visual), but the weld receives no volumetric examination inspection
1.7	3	As-welded surface that receives MT/PT examination and a VT examination (visual), but the weld receives no volumetric examination inspection
2.0	4	Weld has received a partial or full volumetric examination, and the surface has received VT examination, but no MT/PT examination
2.5	5	VT examination only of the surface; no volumetric examination nor MT/PT examination
3.0	6	Volumetric examination only
4.0	7	Weld backsides that are nondefinable and/or receive no examination

GENERAL NOTES:
(a) Volumetric examination is RT or UT in accordance with Part 7.
(b) MT/PT examination is magnetic particle or liquid penetrant examination in accordance with Part 7.
(c) VT examination is visual examination in accordance with Part 7.
(d) See WRC Bulletin 432 for further information.

Figure 19: Fatigue Penalty Factors

Table 5.13
Fatigue Penalty Factors for Fatigue Analysis

Material	K_e [Note (1)]		T_{max} [Note (2)]	
	m	n	°C	°F
Low alloy steel	2.0	0.2	371	700
Martensitic stainless steel	2.0	0.2	371	700
Carbon steel	3.0	0.2	371	700
Austenitic stainless steel	1.7	0.3	427	800
Nickel-chromium-iron	1.7	0.3	427	800
Nickel-copper	1.7	0.3	427	800

NOTES:
(1) Fatigue penalty factor.
(2) The fatigue penalty factor should be used only if all of the following are satisfied:
- The component is not subject to thermal ratcheting.
- The maximum temperature in the cycle is within the value in the table for the material.

$K_{e,k} = 1.0$ (for $\Delta S_{n,k} \leqslant S_{PS}$)

$K_{e,k} = 1.0 + \frac{(1-n)}{n(m-1)}\left(\frac{\Delta S_{n,k}}{S_{PS}} - 1\right)$ (for $S_{PS} < \Delta S_{n,k} < m\, S_{PS}$)

$K_{e,k} = \frac{1}{n}$ (for $\Delta S_{n,k} \geqslant m\, S_{PS}$)

$\Delta S_{n,k}$ is the equivalent stress range, derived from stress linearization, for PL+Pb+Q. S_{PS} is the allowable value as shown on Page 16.

$K_{v,k}$ is the Poisson correction factor.

$$K_{v,k} = \left(\frac{1 - v_e}{1 - v_p}\right)$$

v_e = elastic Poisson's ratio

v_p = plastic Poisson's ratio

$$v_p = max\left[0.5 - 0.2\left(\frac{S_{y,k}}{S_{a,k}}\right), v_e\right]$$

Step 6: Determine the permissible number of cycles, N_k, for the alternating equivalent stress $S_{alt,k}$. Fatigue curves are provided in Div. 2 Annex 3-F, 3-F.1.

<u>Smooth Bar Design Fatigue Curve Usage</u>

Fatigue analysis performed through direct interpretation of the smooth bar fatigue curves found in 3-F.5 requires the calculated stress amplitude, Sa, be corrected for temperature by the ratio of the modulus of elasticity of the given fatigue curve to the value used in the analysis. The equations used to correct Sa for the temperature effect based upon the different material fatigue curves are provided in Table 3-F.1. The temperature-corrected stress amplitude, Sac, is then used to enter the smooth bar fatigue curves to determine the number of allowable cycles, N.

Fatigue life can also be calculated in equation form.

$$N = 10^X$$

Figure 20: Smooth Bar Fatigue Curve Stress Amplitude Correction Equations

Table 3-F.1
Smooth Bar Fatigue Curve Stress Amplitude Correction Equations

Fatigue Curve	Temperature-Corrected Stress Amplitude, S_{ac} MPa	Temperature-Corrected Stress Amplitude, S_{ac} ksi
Figure 3-F.1 Figure 3-F.2 Figure 3-F.3	$195.0\text{ E3}\left(\frac{S_a}{E_T}\right)$	$28.3\text{ E3}\left(\frac{S_a}{E_T}\right)$
Figure 3-F.4 Figure 3-F.5 Figure 3-F.6	$138.0\text{ E3}\left(\frac{S_a}{E_T}\right)$	$20.0\text{ E3}\left(\frac{S_a}{E_T}\right)$
Figure 3-F.7	$195.0\text{ E3}\left(\frac{S_a}{E_T}\right)$	$28.3\text{ E3}\left(\frac{S_a}{E_T}\right)$
Figure 3-F.8 Figure 3-F.9	$206.0\text{ E3}\left(\frac{S_a}{E_T}\right)$	$30.0\text{ E3}\left(\frac{S_a}{E_T}\right)$

Figure 21: Fatigue Calculation Sub-Formulas

3-F.1.2

Fatigue analysis performed using smooth bar fatigue curve models in equation form is provided below. The fatigue curves and the associated equations for different materials are also shown below.

(a) Carbon, Low Alloy, Series 4XX, High Alloy, and High Tensile Strength Steels for temperatures not exceeding 371°C (700°F). The fatigue curve values may be interpolated for intermediate values of the ultimate tensile strength.

$$Y = \log\left[28.3\,\text{E3}\left(\frac{S_a}{E_T}\right)\right] \qquad \text{(3-F.1)}$$

(1) For $\sigma_{uts} \le 552$ MPa (80 ksi) (see Figures 3-F.1M and 3-F.1)

$$X = -4706.5245 + 1813.6228Y + \frac{6785.5644}{Y} - 368.12404Y^2 - \frac{5133.7345}{Y^2} + 30.708204Y^3 + \frac{1596.1916}{Y^3} \quad \text{for } 10^Y \ge 20 \qquad \text{(3-F.2)}$$

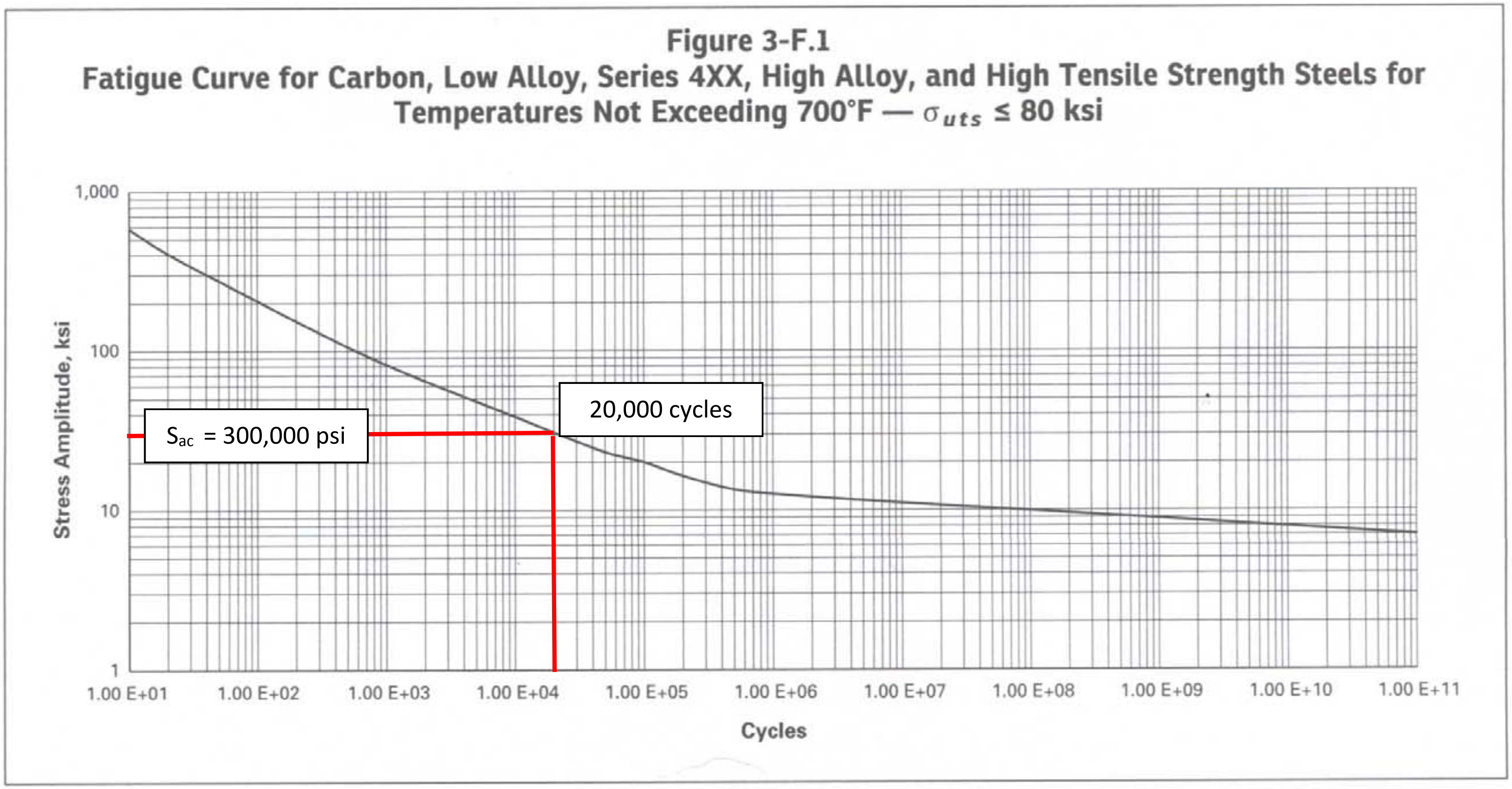
$$X = \frac{38.1309 - 60.1705Y^2 + 25.0352Y^4}{1 + 1.80224Y^2 - 4.68904Y^4 + 2.26536Y^6} \quad \text{for } 10^Y < 20 \qquad \text{(3-F.3)}$$

(2) For $\sigma_{uts} = 793$ MPa to 892 MPa (115 ksi to 130 ksi) (see Figures 3-F.2M and 3-F.2)

$$X = \frac{5.37689 - 5.25401Y + 1.14427Y^2}{1 - 0.960816Y + 0.291399Y^2 - 0.0562968Y^3} \quad \text{for } 10^Y \ge 43 \qquad \text{(3-F.4)}$$

$$X = \frac{-9.41749 + 14.7982Y - 5.94Y^2}{1 - 3.46282Y + 3.63495Y^2 - 1.21849Y^3} \quad \text{for } 10^Y < 43 \qquad \text{(3-F.5)}$$

Figure 22: Smooth Bar Fatigue Curve



Step 7: Determine the fatigue damage for the kth cycle, where the actual number of repetitions of the kth cycle is n_k. Nk is the allowable cycles just calculated.

$$D_{f,k} = \frac{n_k}{N_k}$$

Step 8: Repeat the N_k calculation each of the subsequent k^{th} cycles.

Step 9: Compute the accumulated fatigue damage using Miner's rule. The location in the component is acceptable for continued operation if this equation is satisfied. (M equals number of all cycles.)

$$D_f = \sum_{k=1}^{M} D_{f,k} \leq 1.0$$

Step 10: Repeat all previous steps for each point of interest in the FEA model.

*** Keep in mind that the stress and life cycle results are highly dependent upon mesh density levels, mesh quality and element type, points of singularities, and false readings for tie constraints, couplings, etc.

ASME Section VIII Div. 2 5.5.4 Fatigue Assessment – Elastic-Plastic Stress Analysis and Equivalent Strains

The Effective Strain Range is used to evaluate the fatigue damage for results obtained from an elastic-plastic stress analysis. The Effective Strain Range is calculated for each cycle in the loading histogram using either cycle-by-cycle analysis or the Twice Yield Method. For the cycle-by-cycle analysis, a cyclic plasticity algorithm with kinematic hardening shall be used.

Twice Yield Method

1. Performed in a single loading step (zero load to full load).
2. Materials use a stabilized cyclic stress-strain range curve model.
3. Model output on the plots is directly stress range and strain range.
4. Kinematic hardening material property not required.
5. Within 2Sy, a component can enter elastic shakedown, meaning after some initial plasticity, the stresses cycle elastically.

Cycle-by-Cycle Analysis

1. FEA model requires being cycled multiple times (typically 5-10 times).
2. Materials use a stabilized stress-strain curve model.
3. Kinematic hardening material property is required. Kinematic hardening is the ramp of the cyclic stress-strain curve from the yield point to the true failure stress. (Unfortunately, the not as simple to enter into FEA program.)
4. Above 2Sy, there can be either plastic shakedown, meaning plastic equal plasticity each cycle, or shakedown, a progressive plasticity to failure.

Figure 23: Smooth Bar Fatigue Curve

3-D.4 CYCLIC STRESS STRAIN CURVE

The cyclic stress–strain curve of a material (i.e., strain amplitude versus stress amplitude) may be represented by eq. (3-D.14). The material constants for this model are provided in Table 3-D.2.

Cycle-by-Cycle Analysis

$$\varepsilon_{ta} = \frac{\sigma_a}{E_y} + \left[\frac{\sigma_a}{K_{css}}\right]^{\frac{1}{n_{css}}} \quad (3\text{-D.14})$$

The hysteresis loop stress–strain curve of a material (i.e., strain range versus stress range) obtained by scaling the cyclic stress–strain curve by a factor of two is represented by eq. (3-D.15). The material constants provided in Table 3-D.2 are also used in this equation.

Twice Yield

$$\varepsilon_{tr} = \frac{\sigma_r}{E_y} + 2\left[\frac{\sigma_r}{2K_{css}}\right]^{\frac{1}{n_{css}}} \quad (3\text{-D.15})$$

Table 3-D.2
Cyclic Stress–Strain Curve Data

Material Description	Temperature, °F	n_{css}	K_{css}, ksi
Carbon Steel (0.75 in. — base metal)	70	0.128	109.8
	390	0.134	105.6
	570	0.093	107.5
	750	0.109	96.6
Carbon Steel (0.75 in. — weld metal)	70	0.110	100.8
	390	0.118	99.6
	570	0.066	100.8
	750	0.067	79.6
Carbon Steel (2 in. — base metal)	70	0.126	100.5
	390	0.113	92.2
	570	0.082	107.5
	750	0.101	93.3
Carbon Steel (4 in. — base metal)	70	0.137	111.0
	390	0.156	115.7
	570	0.100	108.5
	750	0.112	96.9
1Cr-$^1/_2$Mo (0.75 in. — base metal)	70	0.116	95.7
	390	0.126	95.1
	570	0.094	90.4
	750	0.087	90.8
1Cr-$^1/_2$Mo (0.75 in. — weld metal)	70	0.088	96.9
	390	0.114	102.7
	570	0.085	99.1
	750	0.076	86.9
1Cr-$^1/_2$Mo (0.75 in. — base metal)	70	0.105	92.5
	390	0.133	99.2
	570	0.086	88.0
	750	0.079	83.7

Step 1: Generate either a Twice Yield or Cycle-by-Cycle elastic-plastic FEA model.

Step 2: Calculate $\Delta_{Sp,k}$ and $\Delta\varepsilon_{peq,k}$, plus E_{yak}. Capture max stress and strain tensors, at point of interest.

$$(\Delta S_{p,k}) = \frac{1}{\sqrt{2}}\left[\left(\Delta\sigma_{11,k} - \Delta\sigma_{22,k}\right)^2 + \left(\Delta\sigma_{11,k} - \Delta\sigma_{33,k}\right)^2 + \left(\Delta\sigma_{22,k} - \Delta\sigma_{33,k}\right)^2 + 6\left(\Delta\sigma_{12,k}^2 + \Delta\sigma_{13,k}^2 + \Delta\sigma_{23,k}^2\right)\right]^{0.5}$$

$$\Delta\varepsilon_{peq,k} = \frac{\sqrt{2}}{3}\left[\left(\Delta p_{11,k} - \Delta p_{22,k}\right)^2 + \left(\Delta p_{22,k} - \Delta p_{33,k}\right)^2 + \left(\Delta p_{33,k} - \Delta p_{11,k}\right)^2 + 1.5\left(\Delta p_{12,k}^2 + \Delta p_{23,k}^2 + \Delta p_{31,k}^2\right)\right]^{0.5}$$

Δp_{ij} is the plastic strain range tensor, calculated similarly as for the stress strain range $\Delta_{Sp,k}$ previously defined (p11 mth cycle – p11 nth cycle for example for Δp_{11}.). For Twice Yield $\Delta_{Sp,k}$ and $\Delta\varepsilon_{peq,k}$ are taken directly off of the FEA stress plot!

E_{yak} is the modulus of elasticity at point of interest at the mean cycle temperature.

Step 3: Calculate the Effective Strain Range for the kth cycle.

$$\Delta\varepsilon_{eff,k} = \frac{\Delta S_{p,k}}{E_{ya,k}} + \Delta\varepsilon_{peq,k}$$

Step 4: Determine the effective alternating equivalent stress for the kth cycle.

$$S_{alt,k} = \frac{E_{ya,k} * \Delta\varepsilon_{eff,k}}{2}$$

Steps 5: Same as Steps 6-10 for Elastic Stress Analysis Method.

Twice Yield FEA Example

Twice Yield Material Properties

The ASME Section VIII Div. 2 Twice Yield method is used to determine stress and strain ranges. Material properties are based on the hysteresis loop stress-strain curve of plain carbon steel (stress range vs strain range), which is obtained by scaling the cyclic stress-strain curve by a factor of two. As a conservative approach, the "weld metal" values were used. ASME Section VIII Div. 2 Section 3-D.4 provide formula and data for determining these material properties. Equation (3-D.15) is copied and shown below:

$$\varepsilon_{tr} = \frac{\sigma_r}{E_y} + 2\left[\frac{\sigma_r}{2K_{css}}\right]^{\frac{1}{n_{css}}}$$

Where,

ε_{tr}	= total true strain range
σ_r	= stress range
E_y	= modulus of elasticity at temperature
K_{css}	= material parameter for the cyclic stress-strain curve = 109.8-ksi at 70°F
n_{css}	= material exponent for the cyclic stress-strain curve = 0.128 at 70°F

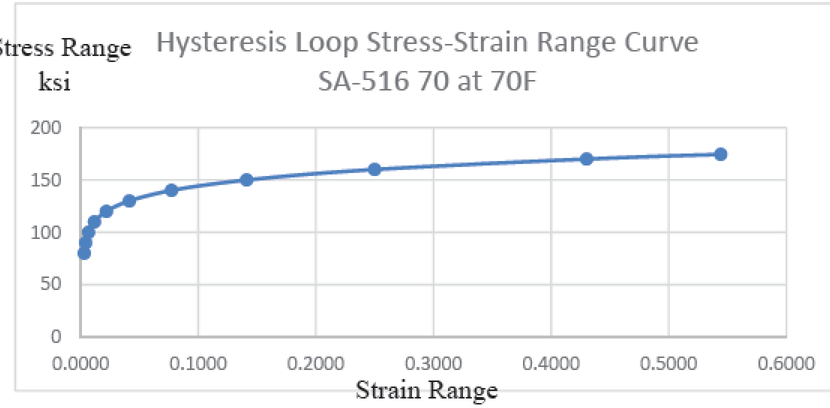


Figure 9: Hysteresis Loop Stress-Strain Range Curve – SA516 70 at 70°F

The resultant curve is shown in Figure 9. The first point on the curve is twice the true yield strength of SA-516 70 at 70°F. Table 5 provides the stress range and plastic strain range data points used for SA-516 70 in this Twice Yield study, limited to 174.5-ksi which is the true stress range at failure true strain range.

Table 5: Twice Yield Material Data Points for SA516-70 at 70°F

Stress Range (ksi)	Plastic Strain Range
76	0
80	0.00045
90	0.00131
100	0.00341
110	0.00811
120	0.01790
130	0.03705
140	0.07267
150	0.13607
160	0.24466
170	0.42455
174.5	0.53836

Modulus of elasticity at the mean cyclic temperature of 70°F, E_{ya}, is 29.4E6-psi.

Per Div. 2 Code, the Effective Strain Range is calculated per Equation 5.43:

$$\Delta\varepsilon_{eff} = \frac{\Delta S_p}{E_{ya}} + \Delta\varepsilon_{PEEQ} = \frac{105468}{27.6E6} + 0.00084 = 0.00466$$

ΔS_p is the equivalent stress range, which is taken directly from the FEA results (Figure 21). E_{ya} is the modulus of elasticity at the mean cyclic temperature. $\Delta\varepsilon_{PEEQ}$ is the equivalent plastic strain range, taken directly from Figure 20.

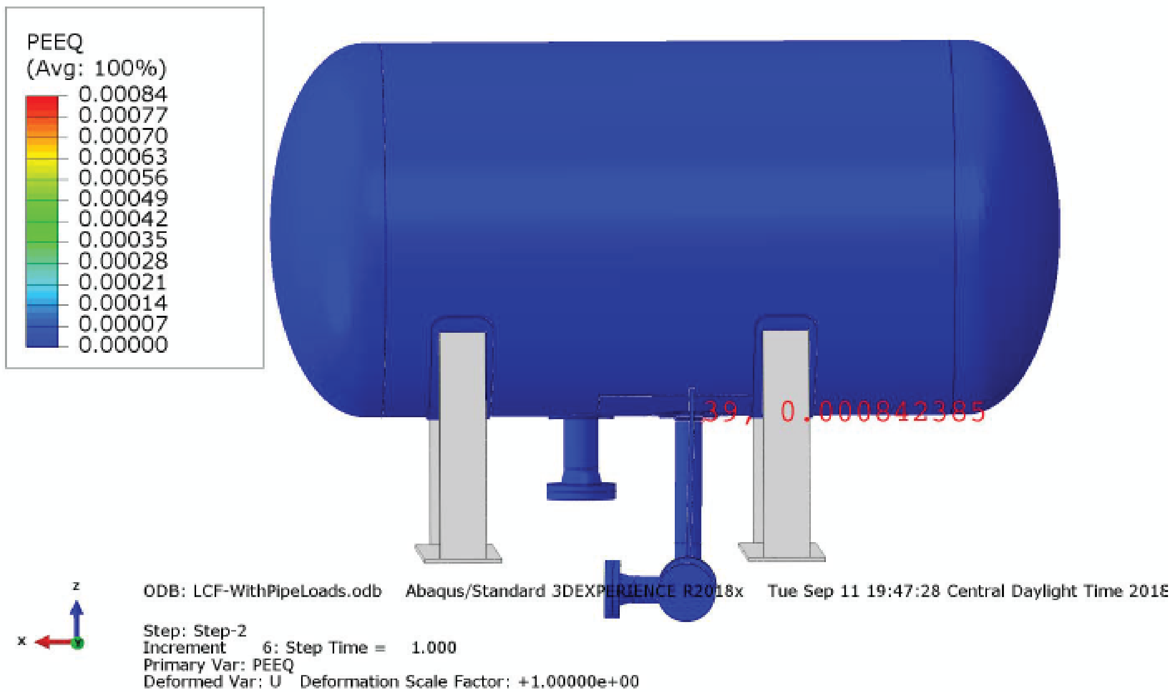


Figure 19: Low Cycle Fatigue – Maximum Equivalent Strain Range

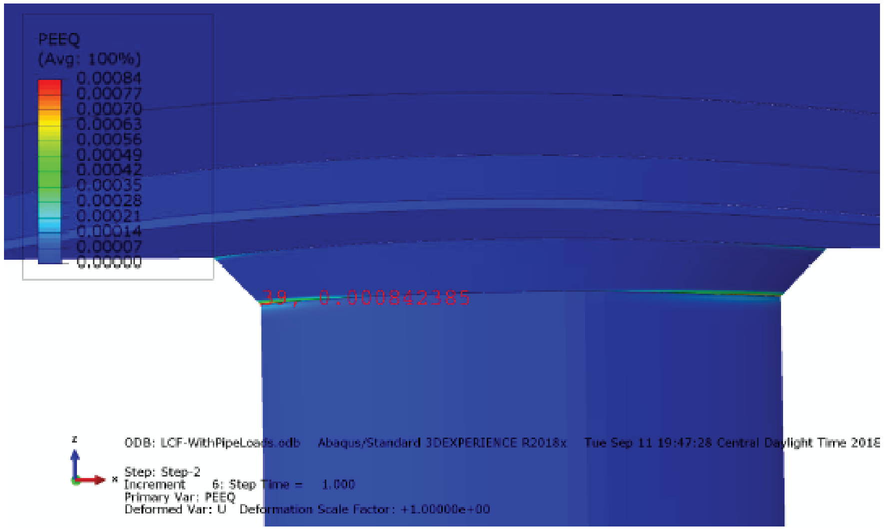


Figure 20: Low Cycle Fatigue – Maximum Equivalent Strain Range Nozzle G1 Outer Fillet Weld

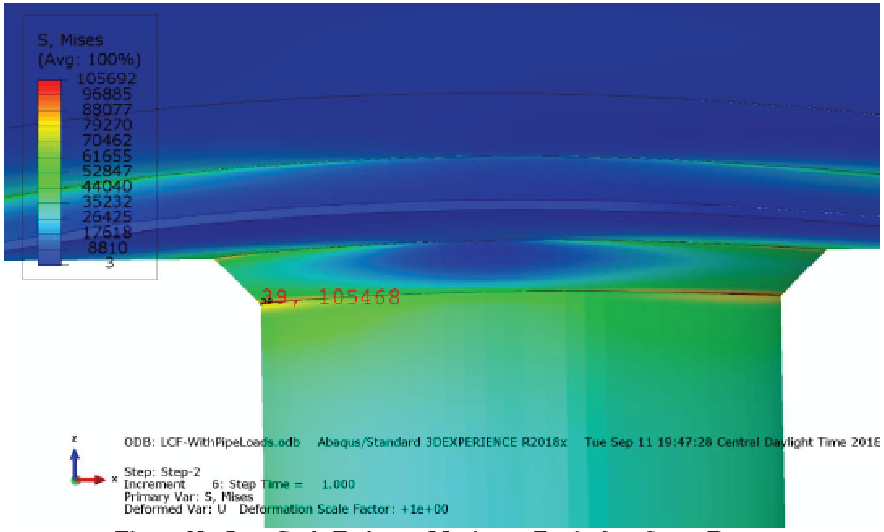


Figure 21: Low Cycle Fatigue – Maximum Equivalent Stress Range Nozzle G1 Outer Fillet Weld

The Effective alternating equivalent stress is per Equation 5.44 from the Div. 2 Code:

$$S_{alt} = \frac{E_{ya} * \Delta\varepsilon_{eff}}{2} = \frac{27.6E6 * 0.00466}{2} = 64{,}300 - psi$$

The permissible number of cycles, N, for S_{alt}, is per the fatigue curves in Annex 3-F, 3-F.3, of the Div. 2 Code, for stainless steel material. Per Figure 21, with S_{alt} plotted, the allowable number of cycles is 5,000.

Figure 3-F.3
Fatigue Curve for Series 3XX High Alloy Steels, Nickel–Chromium–Iron Alloy, Nickel–Iron–Chromium Alloy, and Nickel–Copper Alloy for Temperatures Not Exceeding 800°F

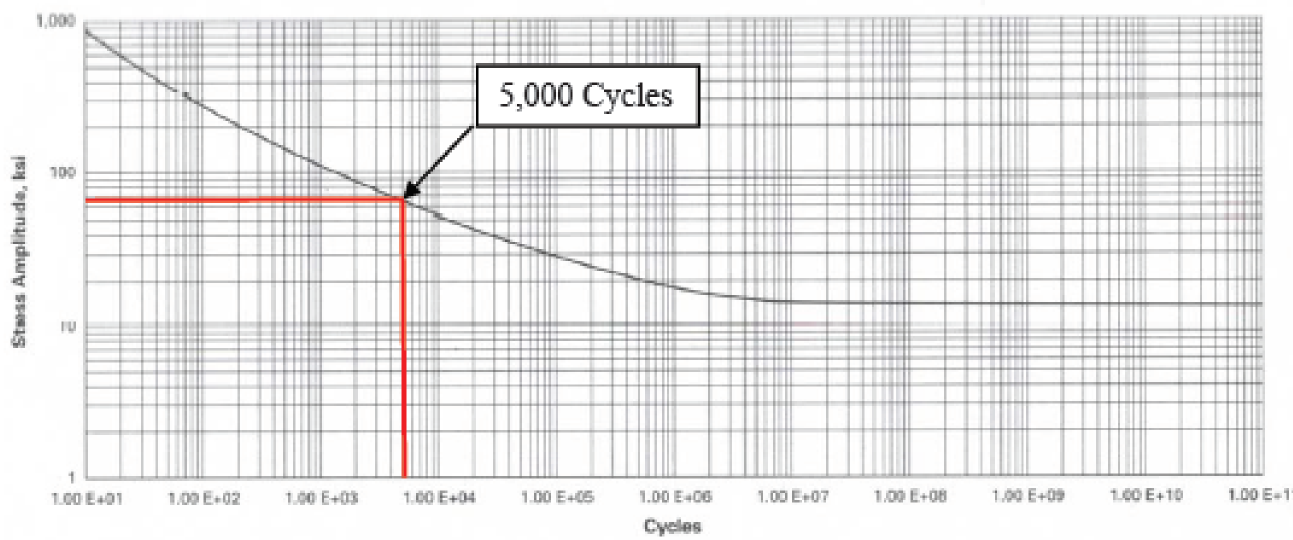


Figure 21: Low Cycle Fatigue – ASME Section VIII Div. 2 Fatigue Curve Stainless Steel Material

Cycle-by-Cycle FEA Example

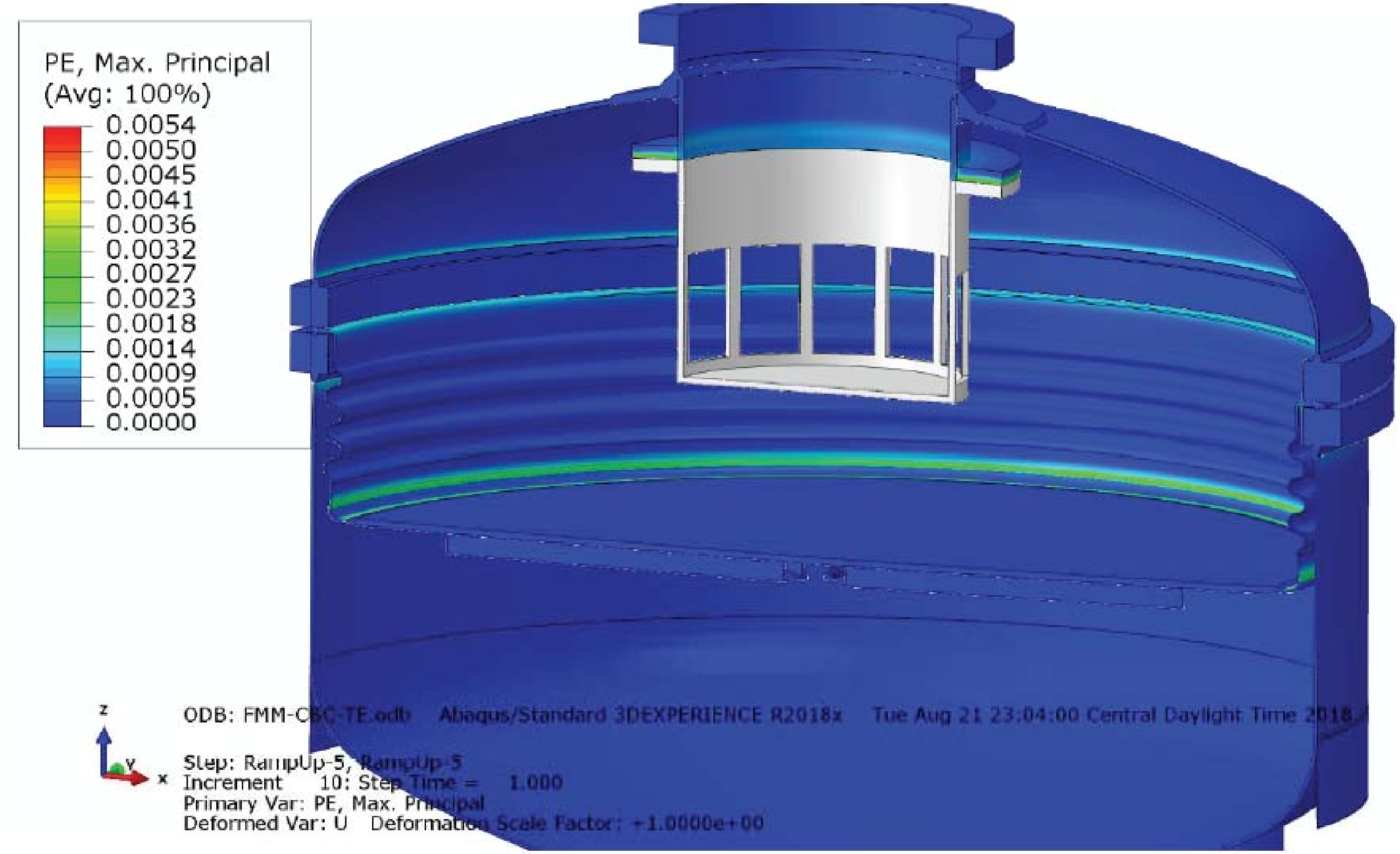


Figure 26: CBC LCF – TE Only – End of 5th Cycle Ramp Up – Plastic Principal Strains

Appendix 2: Stabilized Cyclic Stress Strain Curve Data

As taken from ASME Section VIII Div. 2, 3-D.4, equation 3-D.14, total strain amplitude is the following:

$$\varepsilon_{ta} = \frac{\sigma_a}{E_y} + \left[\frac{\sigma_a}{K_{CSS}}\right]^{\frac{1}{n_{CSS}}}$$

Where,

ε_{ta} = total true strain amplitude
σ_a = total stress amplitude
E_y = modulus of elasticity evaluated at temperature of interest
K_{CSS} = material parameter for the cyclic stress-strain curve model
n_{CSS} = material parameter for the cyclic stress-strain curve model

For Type 304 austenitic stainless steel (the most applicable for 316-Ti), the following constants apply, as taken from ASME Section VIII Div. 2 Table 3-D.2M.

Table A2-1A: Type 304 SS Stabilized Cyclic Curve Data

Temperature °C	n_{CSS}	K_{CSS} MPa
20	0,171	1227
400	0,095	590
500	0,085	550
600	0,090	450
700	0,094	306

For 800-H, the following constants apply, as taken from ASME Section VIII Div. 2 Table 3-D.2M.

Table A2-1B: 800-H Stabilized Cyclic Curve Data

Temperature °C	n_{CSS}	K_{CSS} MPa
20	0,070	631
500	0,085	762
600	0,088	729
700	0,092	553
800	0,080	315

Total strain amplitude is set to specific values ranging from 0 to 2.1% (which equates to 2% plastic strain). Stress amplitude is iteratively determined using Equation 3-D.14. Below is the calculation for 20°C, 400°C, and 500°F. These temperatures are average temperatures between the two extremes of the cycle. For instance, if initial cycle is at ambient (20°F) and the temperature at operating is 580°F, then the curve data to use would be at 300°F. Therefore, curve data between 20°F and 400°F would be interpolated to 300°F.

To calculate Kinematic Hardening data (Table A2-2A/B), a simple one-element FEA model is created. Data pairs of stress and plastic strain from Table A2-3 are entered as half-cycle test data points in the Plasticity-Plastic Hardening-Combined-Half Cycle property box. A data check is initiated in Abaqus to determine the initial estimates of C and γ (located in the *.data file with the "print model definition data" checked in "edit job"). These two parameters (C and γ) are then divided by 1,402 and used in the Plastic Hardening-Combined-Parameters property box.

Table A2-2A: Type 304 SS Abaqus Combined Hardening Kinematic Hardening Data

Yield Stress at Zero Plastic Strain (MPa)	Kinematic Hardening Parameter, C1	Gamma 1	High End Temperature, °C
208	55338	139,62	20
149	69142	289,30	525
145	71904	296,29	660

The "High End Temperature", or T_{upper}, in Table A2-2 is adjusted for AD-2000 T* ($T^* = 0{,}75T_{upper} + 0{,}25T_{lower}$) so that the value in this column can be directly related to the high-end operating temperature in the FEA model.

Table A2-2B: 800H Abaqus Combined Hardening Kinematic Hardening Data

Yield Stress at Zero Plastic Strain (MPa)	Kinematic Hardening Parameter, C1	Gamma 1	High End Temperature, °C
172	96777	333,89	20
109	122989	298,27	980
103	126858	303,50	1180

The "High End Temperature", or T_{upper}, in Table A2-2 is adjusted for AD-2000 T* ($T^* = 0{,}75T_{upper} + 0{,}25T_{lower}$) so that the value in this column can be directly related to the high-end operating temperature in the FEA model.

Table A2-3A: Stabilized Cyclic Stress-Strain Amplitude Data Pairs (Stress-Plastic Strain) – 304SS

20C							
Sigma(o)	208		TrueStrain (t)	TrueStress	Calculated e(t)	Stress	PlasticStrain
E	1.95E+05		0.001	208	0.001	208	0.000000
e(o)	0.001067		0.002	267	0.002	267	0.000933
ncss	0.171		0.003	354	0.003	354	0.001933
Kcss	1227		0.004	401	0.004	401	0.002933
			0.005	434	0.005	434	0.003933
			0.006	459	0.006	459	0.004933
			0.007	479	0.007	479	0.005933
			0.008	496	0.008	496	0.006933
			0.009	510	0.009	510	0.007933
			0.010	523	0.010	523	0.008933
			0.011	535	0.011	535	0.009933
			0.012	546	0.012	546	0.010933
			0.013	555	0.013	555	0.011933
			0.014	564	0.014	564	0.012933
			0.015	573	0.015	573	0.013933
			0.016	581	0.016	581	0.014933
			0.017	588	0.017	588	0.015933
			0.018	595	0.018	595	0.016933
			0.019	602	0.019	602	0.017933
			0.020	608	0.020	608	0.018933
			0.021	614	0.021	614	0.019933

400C							
Sigma(o)	149		TrueStrain (t)	TrueStress	Calculated e(t)	Stress	PlasticStrain
E	1.69E+05		0.001	149	0.001	149	0.000000
e(o)	0.000882		0.002	241	0.002	241	0.000933
ncss	0.095		0.003	298	0.003	298	0.001933
Kcss	590		0.004	321	0.004	321	0.002933
			0.005	335	0.005	335	0.003933
			0.006	345	0.006	345	0.004933
			0.007	353	0.007	353	0.005933
			0.008	360	0.008	360	0.006933
			0.009	365	0.009	365	0.007933
			0.010	370	0.010	370	0.008933
			0.011	375	0.011	375	0.009933
			0.012	379	0.012	379	0.010933
			0.013	382	0.013	382	0.011933
			0.014	386	0.014	386	0.012933
			0.015	389	0.015	389	0.013933
			0.016	392	0.016	392	0.014933
			0.017	394	0.017	394	0.015933
			0.018	397	0.018	397	0.016933
			0.019	399	0.019	399	0.017933
			0.020	401	0.020	401	0.018933
			0.021	404	0.021	404	0.019933

There are two areas of interest as identified in Figure 27A (equivalent plastic strain) and Figure 27B (maximum principal strain), Nodes 81 and 10680.

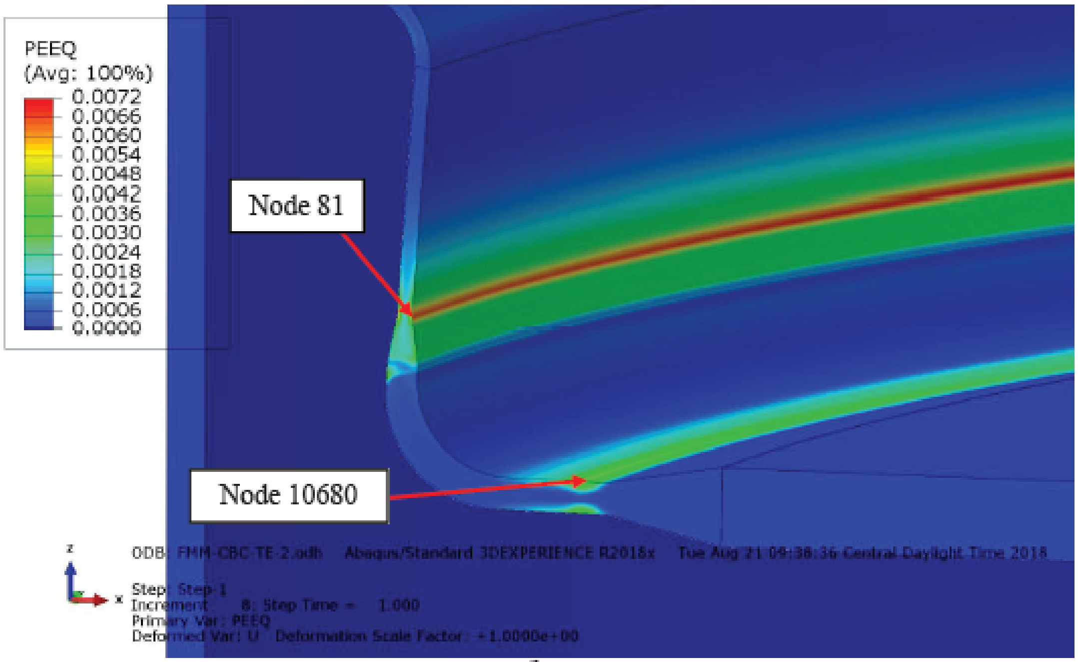


Figure 27A: CBC LCF – TE Only – End of 5th Cycle Ramp Up – Areas of Interest - PEEQ

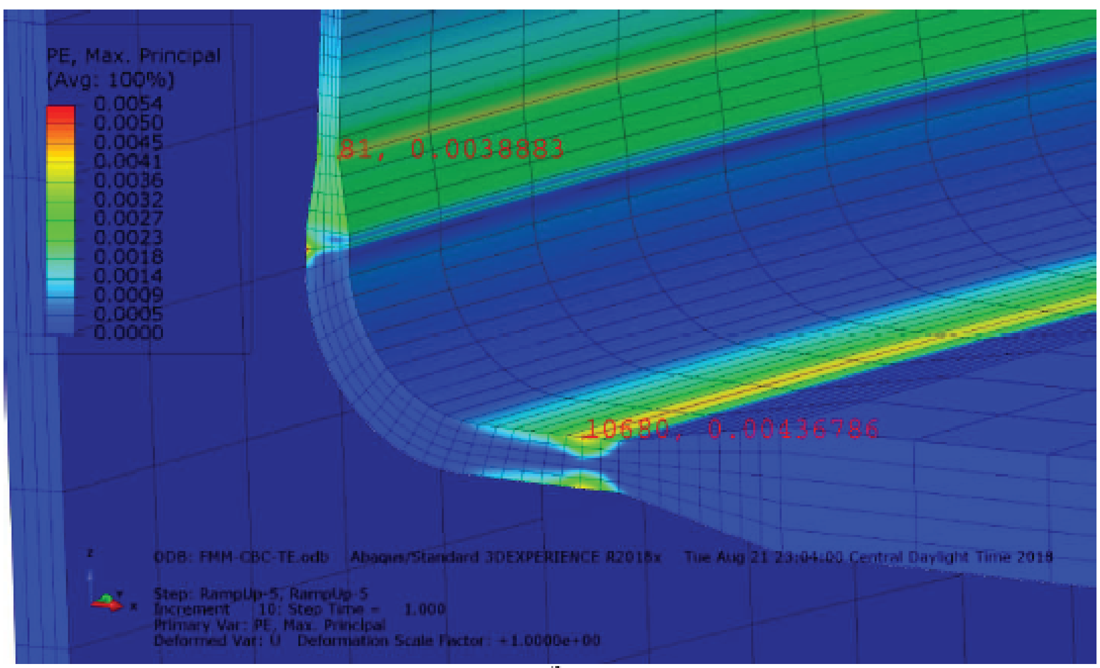


Figure 27B: CBC LCF – TE Only – End of 5th Cycle Ramp Up – Areas of Interest - PEEQ

Equivalent plastic strain was plotted for both nodal points of interest (Figure 27C), revealing that Nodal Point 10680 is in Elastic Shakedown. That is, after a couple cycles, there is no further plastic accumulation. Node 81 shows that it is in Plastic Shakedown, which is evident by the even increments of plastic accumulation for each cycle.

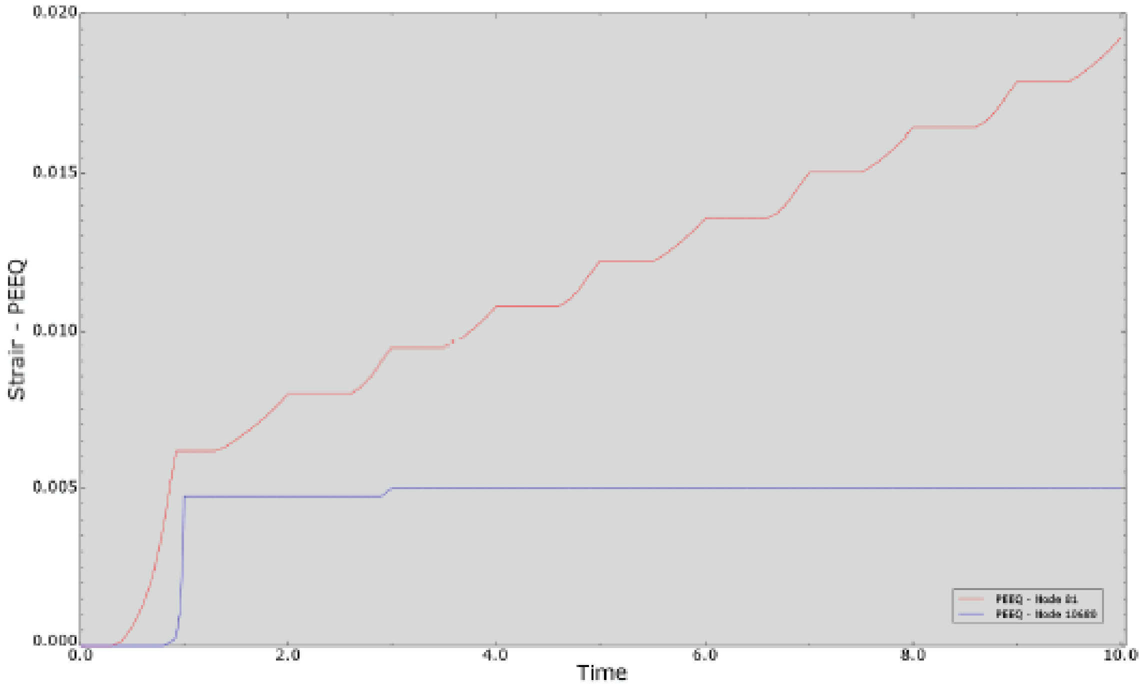


Figure 27C: CBC LCF – TE Only – PEEQ Cycle Plot at Nodes 81 and 10680

Principal strains and principal stresses are plotted for Nodal Point 81 in Figure 28A and 28B. In addition to the principal strains, both stress and strain tensors at this nodal point were obtained at the beginning and end of the 5th cycle.

Following Figure 28B is the AD 2000 fatigue calculations for Nodal Point 81, which is not at a weld. The allowable number of cycles is just over 5000.

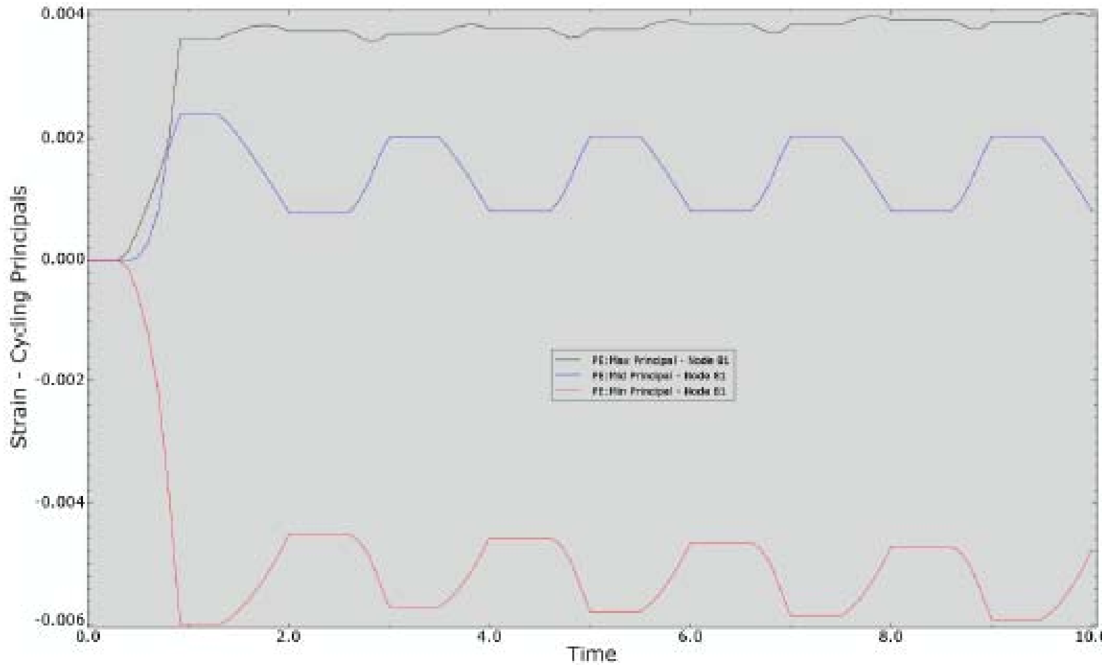


Figure 28A: CBC LCF – TE Only – Principal Strain Cycle Plots at Nodes 81

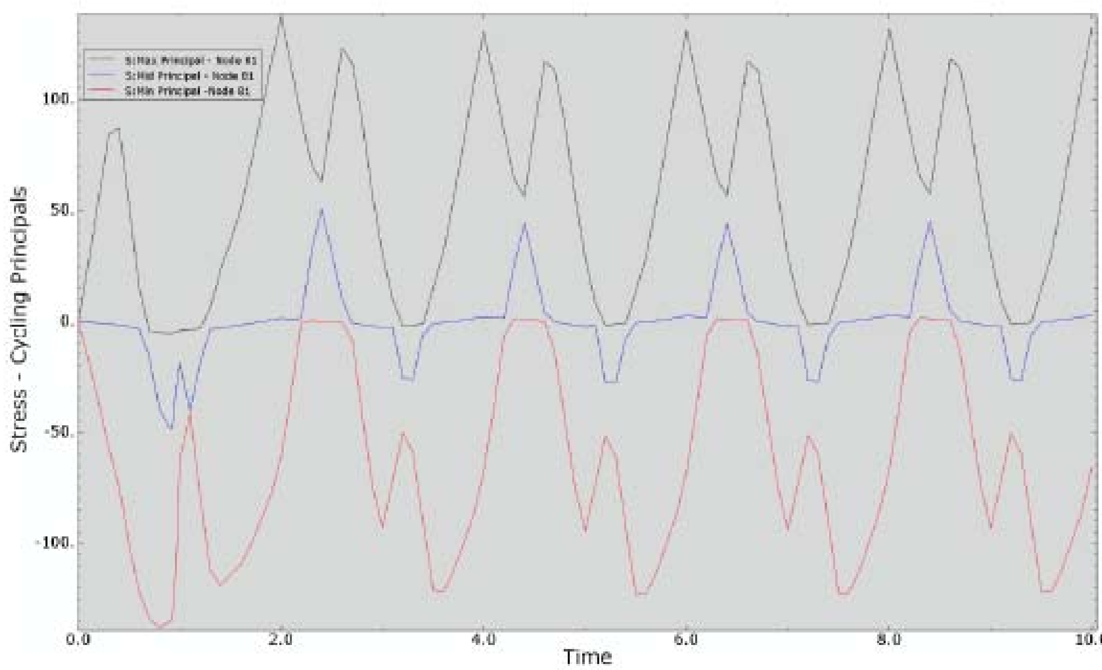


Figure 28B: CBC LCF – TE Only – Principal Stress Cycle Plots at Nodes 81

Hexion-Duisburg Silver Reactor - Fatigue Calculations
Thermal Expansion Loading Only

Data Section

Material - 800H [1.4958]

$T_H := 700$ °C

$T_L := 0$ °C

$Tstar := 0.75 \cdot T_H + 0.25\ T_L = 525$ °C

$E_{Tstar} := 183000$ MPa

$Rm := 500$ MPa Min tensile strength @ 20 °C

$Rp_{02Tstar} := 77$ MPa

$Rz := 200$ for rolled or extruded

$s_e := 4\ mm$

Strain Data at Node 81 of Basket Side Wall

Plastic Strain Tensor

Ambient/No Loads	Operating/With Loads
$p_{11L} := 0.00385$	$p_{11H} := 0.00387$
$p_{22L} := 0.00081$	$p_{22H} := 0.00203$
$p_{33L} := -0.00465$	$p_{33H} := -0.00590$
$p_{12L} := 0.0$	$p_{12H} := 0.0$
$p_{13L} := 0.00125$	$p_{13H} := 0.00296$
$p_{23L} := 0.0$	$p_{23H} := 0.0$

Thigh Principal Stresses (MPa)

$s_{1H} := 30.294$

$s_{2H} := -1.983$

$s_{3H} := -93.313$

Stress Strain Tensor (MPa)

Ambient/No Loads	Operating/With Loads
$s_{11L} := 3.811$	$s_{11H} := -2.089$
$s_{22L} := -66.464$	$s_{22H} := 30.294$
$s_{33L} := 130.600$	$s_{33H} := -93.207$
$s_{12L} := 0.030$	$s_{12H} := -0.015$
$s_{13L} := -10.867$	$s_{13H} := 1.838$
$s_{23L} := 0.017$	$s_{23H} := -0.008$

Fatigue Calculations

Stress and Strain Tensor Delta Calculations for FEA Cylce 5

$\Delta p_{11} := p_{11H} - p_{11L} = 0.00002$ $\quad \Delta s_{11} := s_{11H} - s_{11L} = -5.9$

$\Delta p_{22} := p_{22H} - p_{22L} = 0.00122$ $\quad \Delta s_{22} := s_{22H} - s_{22L} = 96.758$

$\Delta p_{33} := p_{33H} - p_{33L} = -0.00125$ $\quad \Delta s_{33} := s_{33H} - s_{33L} = -223.807$

$\Delta p_{12} := p_{12H} - p_{12L} = 0$ $\quad \Delta s_{12} := s_{12H} - s_{12L} = -0.045$

$\Delta p_{13} := p_{13H} - p_{13L} = 0.00171$ $\quad \Delta s_{13} := s_{13H} - s_{13L} = 12.705$

$\Delta p_{23} := p_{23H} - p_{23L} = 0$ $\quad \Delta s_{23} := s_{23H} - s_{23L} = -0.025$

Equivalent Plastic Strain for FEA Cycle 5

$$\Delta\varepsilon_{peq} := \frac{\sqrt{2}}{3} \cdot \left[\left(\Delta p_{11} - \Delta p_{22}\right)^2 + \left(\Delta p_{22} - \Delta p_{33}\right)^2 + \left(\Delta p_{33} - \Delta p_{11}\right)^2 + 1.5 \left(\Delta p_{12}{}^2 + \Delta p_{23}{}^2 + \Delta p_{13}{}^2\right) \right]^{0.5} = [0.002]$$

$$\Delta s_p := \frac{1}{\sqrt{2}} \cdot \left[\left(\Delta s_{11} - \Delta s_{22}\right)^2 + \left(\Delta s_{11} - \Delta s_{33}\right)^2 + \left(\Delta s_{22} - \Delta s_{33}\right)^2 + 6 \left(\Delta s_{12}{}^2 + \Delta s_{13}{}^2 + \Delta s_{23}{}^2\right) \right]^{0.5} = [284.4]\ MPa$$

Total Effective Strain Range for FEA Cycle 5

$$\Delta\varepsilon_{eff} := \frac{\Delta s_p}{E_{Tstar}} + \Delta\varepsilon_{peq} = [0.003]$$

In AD 2000, this is 2* ε_{ages}.