Background for 620-1024 Expansion of Table R-6

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Revision: C

Purpose

- Summarize method of generating and expanding Table R-6
- Compare results from smooth bar fatigue and welded joint fatigue methods from ASME Section VIII Div 2 Part 5.5 to the assumed 1300 cycles used for generating Table R-6
  - Run for two shell/annular plate designs in accordance with the upper bounds of the existing and proposed API 620 Table R-6 in 620-1024 Expand Table R-6 for Thicknesses up to 2.5in
- Compare the resulting number of cycles with the assumed 1300 cycles to validate the revised Table R-6.

Generating Table R-6: Procedure

Determining Shell Design

- The first step was to determine shell designs with a first course thickness and design stress matching each intersecting point in the existing Table R-6.
- These designs were back calculated from the $\sigma = 2.6*D*H*(H*G) / t$ equation provided in Note b of Table R-6.
- The lesser height of the following design restrictions were considered to maximize the annular plate thickness requirements within reasonable limits. The lesser height of a design resulting in
  - Limiting bearing pressure to 6000 psf bearing pressure
  - Limit liquid height over diameter ratio to 1.2

Note: Early on in the effort, a comparison of required annular plate thicknesses for varying tank proportions given a specific first shell ring thickness and design stress showed that taller tanks required thicker annular plates. This is intuitive since a taller tank will have more hydrostatic head that will force more rotation at the corner joint.

Generating Table R-6: Procedure

Shell Design Assumptions:

- The specific gravity (G) is used as 0.610 throughout this analysis.
- The tank designs assume 1ft of freeboard above the liquid level required to obtain the design stress
- The number of shell rings are selected to have a width close to 10 feet.

Generating Table R-6: Procedure

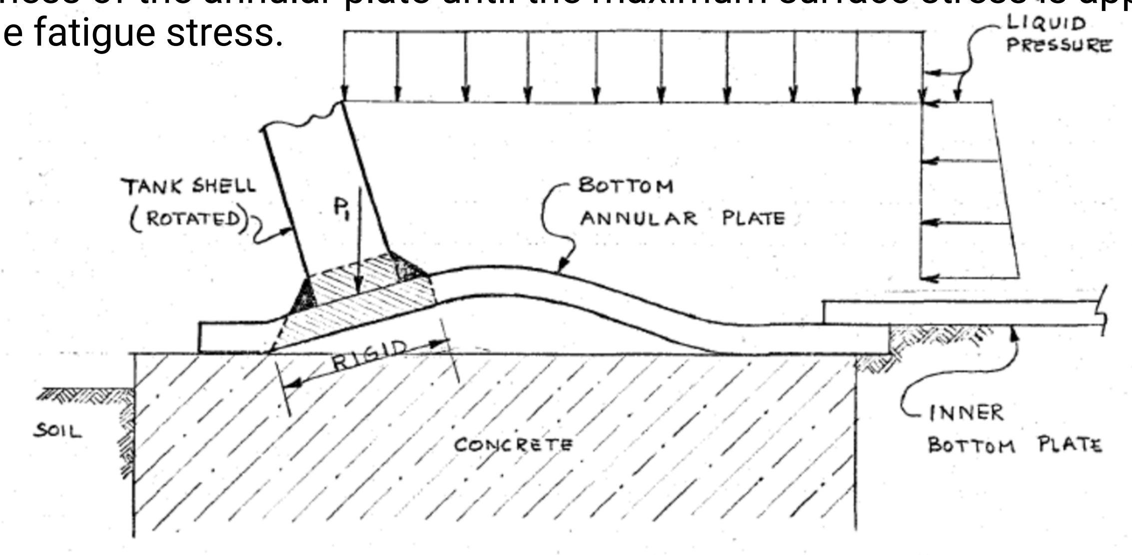
Determining Annular Plate Thickness

- The existing table was generated using an annular plate stress analysis described on the next page along with the following surface stress limits.
  - The maximum top surface stress (S_{max}) of the annular plate is limited to approximately 75,000 psi.
    - This limit is associated with 1,300 cycles from the fatigue curves that are currently located in ASME BPVC Section III Appendix 1 Table I-9.1.
    - The number of cycles is a function of S_a, the amplitude of the alternating stress intensity component (i.e one-half of the alternating stress intensity range).
    - Since the top of the annular plate at the inside toe of the fillet weld is exposed, a Fatigue Strength Reduction Factor (FSRF) of 2 is acceptable with some conservatism.
    - The surface stress on the top of the annular plate is assumed zero for the empty case.
    - Therefore, $S_a=(S_{max}-0)/2 * FSRF$, which results in $S_a=S_{max}$=75,000 psi.
- In order to provide a consistent basis for the Table R-6 expansion, the same methodology is used for extrapolation.

Generating Table R-6: Procedure

Annular Plate Stress Analysis

- The analysis reports the maximum surface stress in the annular plate at the inside edge of the inner fillet weld.
- The analysis assumes the shell and annular plate behave elastically and the foundation is infinitely rigid.
- The equilibrium of the annular plate is found by treating the annular plate as a simply supported beam with a length resulting equivalent rotations in the shell and annular plate at the shell-to-annular junction along with zero rotation at the inside edge of the annular.
- The program iterates the thickness of the annular plate until the maximum surface stress is approximately equal to the specified allowable fatigue stress.



Validation: Purpose

While Table R-6 has been expanded using the same approach for the sake of consistency, the basis of that approach is not necessarily the current common practice.

Therefore, it is appropriate to run a more accepted fatigue analysis procedure to prove that the designs resulting from Table R-6 meet or exceed the stated number of 1300 cycles.

Generating Table R-6: Results

The minimum annular plate thicknesses required by the analysis are rounded up to the nearest 1/32 in to be consistent with the existing table. The results rounded up to the nearest 0.01in has also been included.

Thickness	20 000	22 000	24 000	26 000
0.75	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$
1.	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{5}{16}$
1.25	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{5}{16}$	$\frac{3}{8}$
1.5	$\frac{1}{4}$	$\frac{9}{32}$	$\frac{3}{8}$	$\frac{7}{16}$
1.75	$\frac{1}{4}$	$\frac{5}{16}$	$\frac{7}{16}$	$\frac{17}{32}$
2.	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{15}{32}$	$\frac{19}{32}$
2.25	$\frac{9}{32}$	$\frac{13}{32}$	$\frac{17}{32}$	$\frac{11}{16}$
2.5	$\frac{5}{16}$	$\frac{7}{16}$	$\frac{19}{32}$	$\frac{3}{4}$

Thickness	20 000	22 000	24 000	26 000
0.75	0.25	0.25	0.25	0.25
1.	0.25	0.25	0.25	0.31
1.25	0.25	0.25	0.31	0.38
1.5	0.25	0.27	0.36	0.45
1.75	0.25	0.31	0.42	0.53
2.	0.25	0.35	0.47	0.6
2.25	0.27	0.39	0.53	0.67
2.5	0.3	0.43	0.58	0.74

Validation: Example Designs

Two designs were considered:

- Maximum Shell Thickness of existing Table R-6

```
⟨|diameter → 146.44 ft , liquidHeight → 155 ft , specificGravity → 0.61,
 widths → { 9.75 ft , 9.75 ft , 9.75 ft , 9.75 ft , 9.75 ft , 9.75 ft , 9.75 ft ,
   9.75 ft , 9.75 ft , 9.75 ft , 9.75 ft , 9.75 ft , 9.75 ft , 9.75 ft , 9.75 ft , 9.75 ft },
 thickness → { 1.49997 in , 1.40562 in , 1.31127 in , 1.21691 in , 1.12256 in , 1.02821 in , 0.933854 in , 0.839501 in ,
   0.745148 in , 0.650795 in , 0.556442 in , 0.462088 in , 0.367735 in , 0.3125 in , 0.3125 in , 0.3125 in },
 stress → 24000., annularPlate → 0.375 in , filletWeld → 0.375 in |⟩
```

- Maximum Shell Thickness of proposed Table R-6

```
⟨|diameter → 240.108 ft , liquidHeight → 157.559 ft , specificGravity → 0.61,
 widths → { 9.90991 ft , 9.90991 ft , 9.90991 ft , 9.90991 ft , 9.90991 ft , 9.90991 ft , 9.90991 ft , 9.90991 ft ,
   9.90991 ft , 9.90991 ft , 9.90991 ft , 9.90991 ft , 9.90991 ft , 9.90991 ft , 9.90991 ft , 9.90991 ft },
 thickness → { 2.5 in , 2.34276 in , 2.18552 in , 2.02828 in , 1.87103 in , 1.71379 in , 1.55655 in , 1.39931 in ,
   1.24207 in , 1.08483 in , 0.927583 in , 0.770342 in , 0.6131 in , 0.455858 in , 0.375 in , 0.375 in },
 stress → 24000., annularPlate → 19/32 in , filletWeld → 19/64 in , grooveWeld → 19/64 in |⟩
```

Validation: Modeling Procedure

- ANSYS Workbench is used to generate 2D axisymmetric models of the two example tanks described previously. The models consider the inner bottom, annular plate and shell placed on concrete elements
- The concrete elements have a fixed support on the surfaces not in contact with the steel.
- The following boundary is set between the bottom of the steel and the concrete:
  - Frictionless contact elements
  - Program controlled formulation, detection method, penetration tolerance
  - Stabilization damping factor of 0.0
  - Bottom edge of annular plate is the contact body with concrete foundation as target body.
- The bottom plate is restrained with horizontal displacement set to zero at the center of the tank.
- Only the first five rings are modeled.
- In order to consider the delta in stresses from empty to full for an entire cycle, only the hydrostatic pressure is applied to the shell, annular and bottom.
- The weight of the shell and annular is constant and therefore can be excluded from the fatigue analysis.
- 2” outside projection of the annular plate from the shell

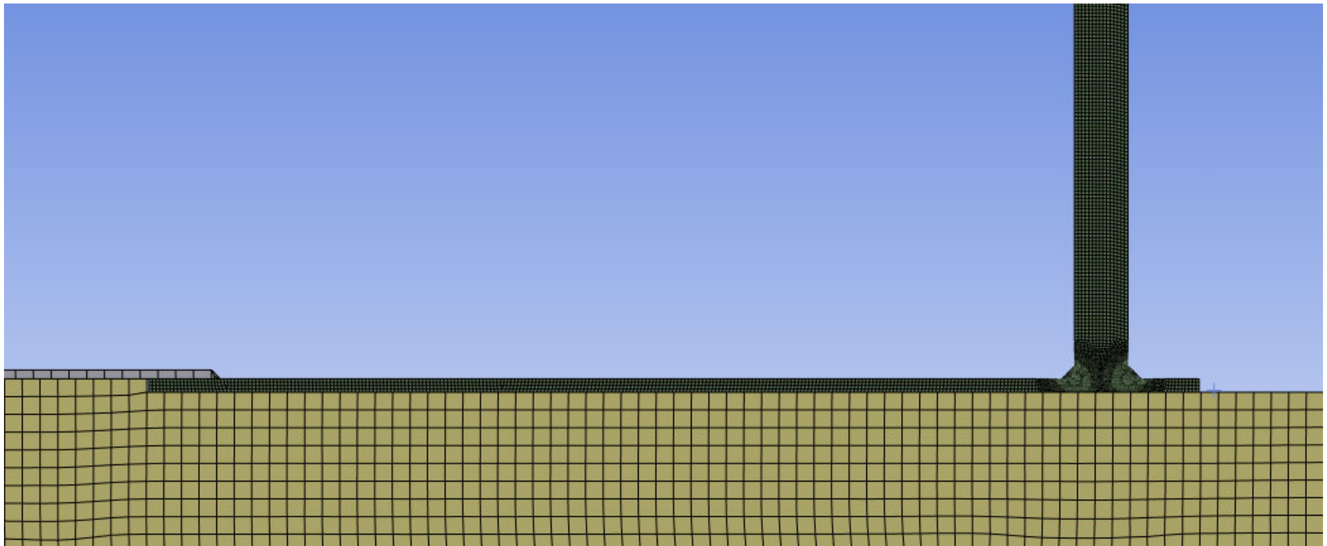
Validation: Modeling Boundary Conditions

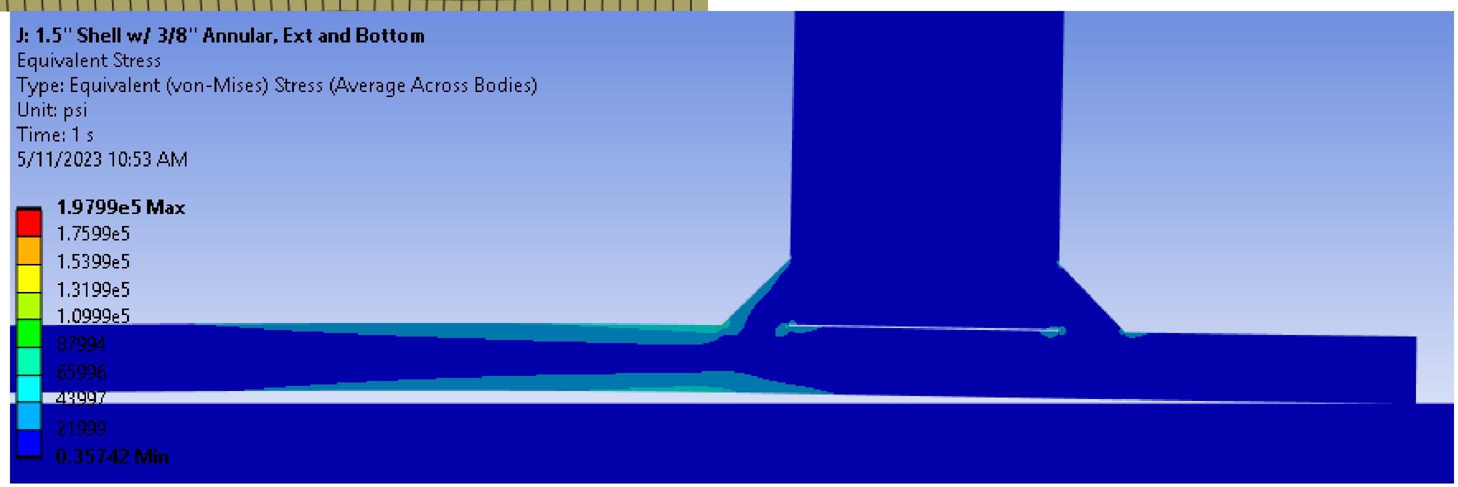
- ANSYS Workbench is used to generate 2D axisymmetric models of the two example tanks described previously. The models consider the inner bottom, annular plate and shell placed on concrete elements
- The concrete elements have a fixed support on the surfaces not in contact with the steel.
- A frictionless contact boundary is set between the bottom of the steel and the concrete.
- The bottom plate is restrained with horizontal displacement set to zero at the center of the tank.
- Only the first five rings are modeled.
- In order to consider the delta in stresses from empty to full for an entire cycle, only the hydrostatic pressure is applied to the shell, annular and bottom.
- The weight of the shell and annular is constant and therefore can be excluded from the fatigue analysis.
- 2” outside projection of the annular plate from the shell

Validation: Evaluation Procedure

- There are two Stress Classification Lines (SCL) that are evaluated for the Smooth Bar Fatigue and Welded Joint Fatigue approaches in accordance with ASME Section VIII Div 2:
  - SCL 1: Through the annular plate at the inside toe of the inner fillet weld
  - SCL 2: Through the crack plane of the inside weld
    - SCL 2a: Exposed Surface
    - SCL 2b: Unexposed Surface
  - The SCL through the shell was not included in the summary. The shell is significantly thicker and will not govern.
- The membrane and bending stresses are determined using linearized normal stresses instead of the linearized equivalent stresses in order to obtain the structural stress normal to the crack plane.
- This excludes any effects of the peak stresses.
- The resulting surface stress was shown to be consistent with extrapolating a sigma_x surface stress at the stress concentration from multiple sigma_x surfaces stresses at different distances from the weld.

Validation: 1.5” Shell Design with 3/8” Annular

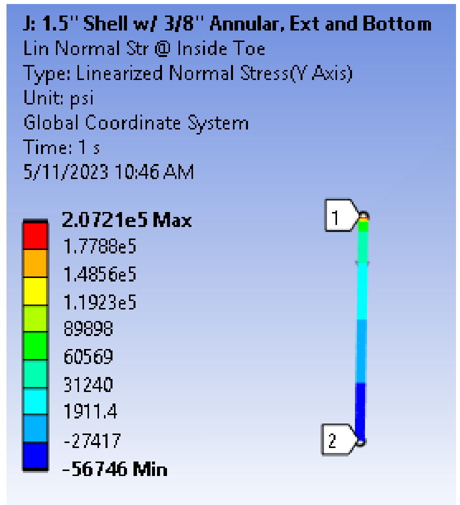


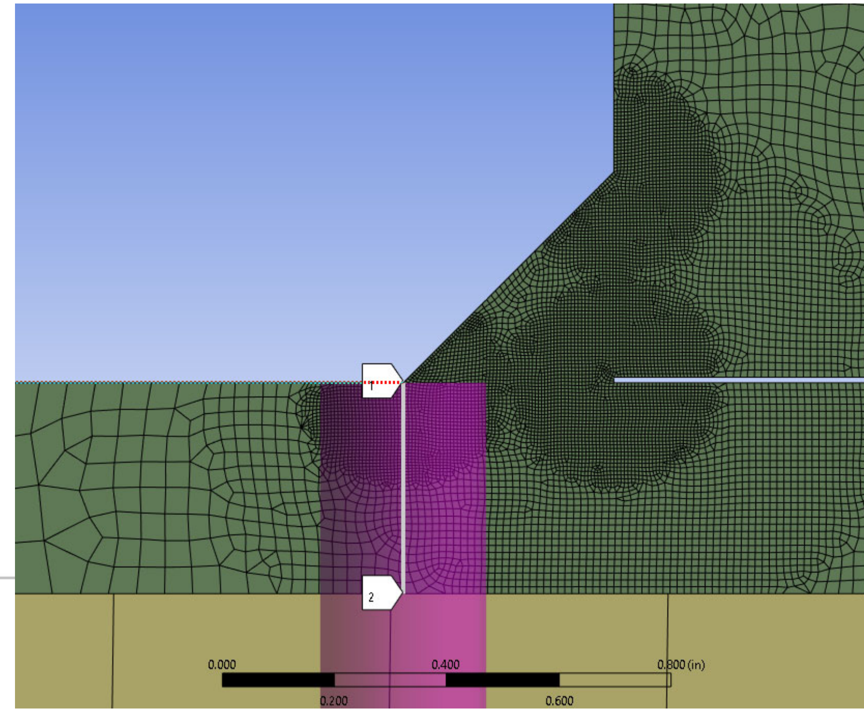


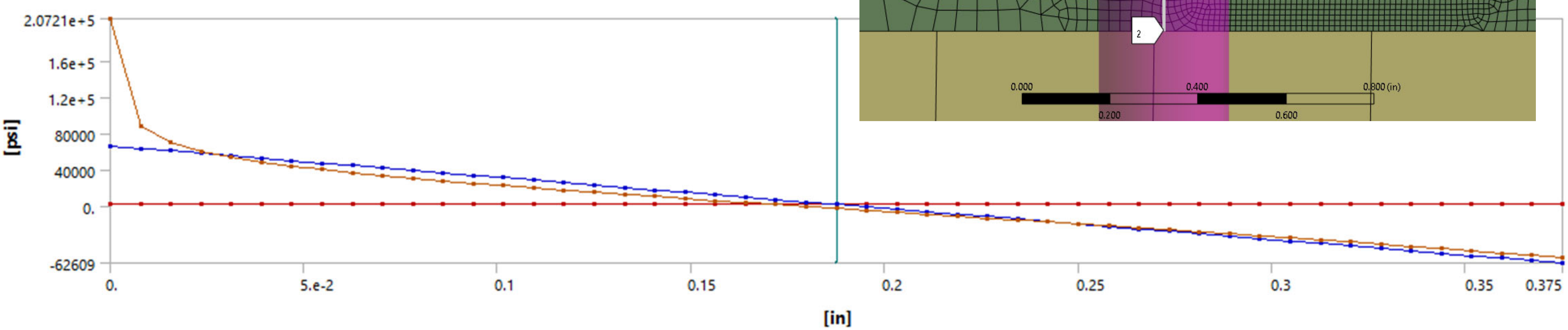
Validation: 1.5” Shell Design with 3/8” Annular

SCL 1

Results	
Membrane	2014.3 psi
Bending (Inside)	64623 psi
Bending (Outside)	-64623 psi
Membrane+Bending (Inside)	66637 psi
Membrane+Bending (Center)	2014.3 psi
Membrane+Bending (Outside)	-62609 psi
Peak (Inside)	1.4058e+005 psi
Peak (Center)	-4402.6 psi
Peak (Outside)	5862.5 psi
Total (Inside)	2.0721e+005 psi
Total (Center)	-2388.3 psi
Total (Outside)	-56746 psi



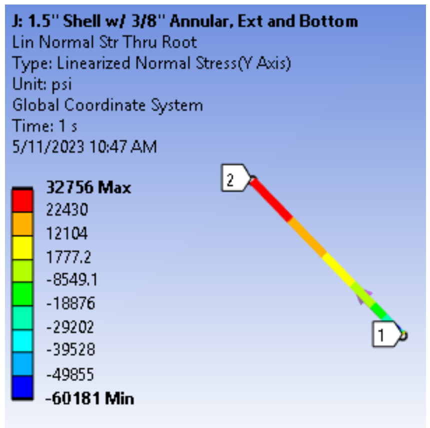


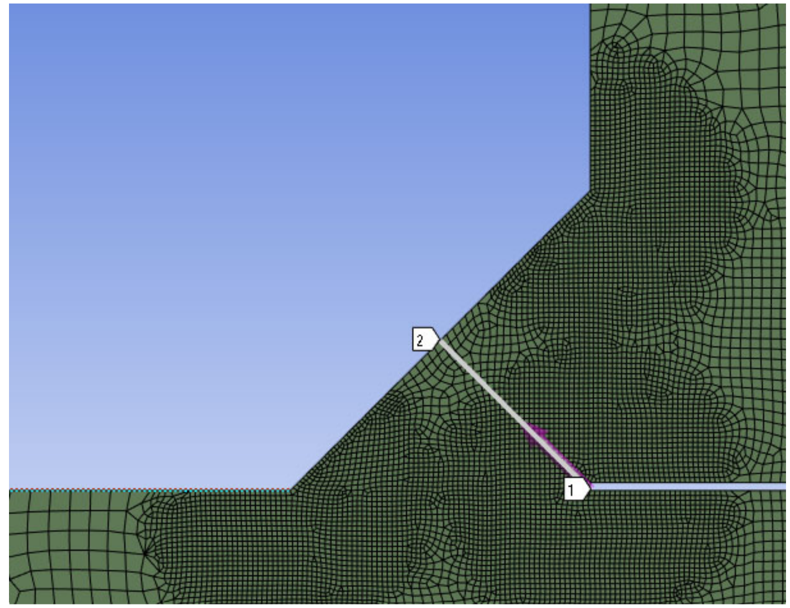


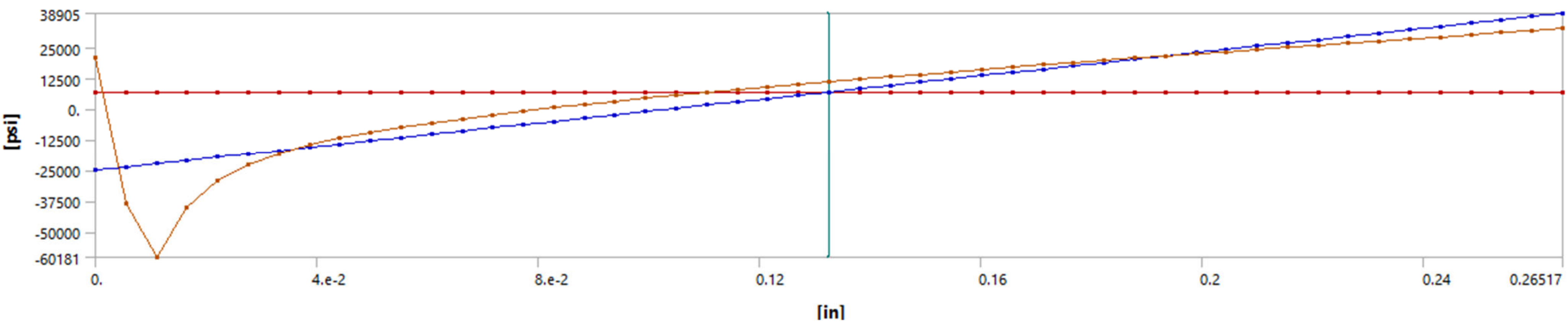
Validation: 1.5” Shell Design with 3/8” Annular

SCL 2

Results	
Membrane	6989.2 psi
Bending (Inside)	-31914 psi
Bending (Outside)	31916 psi
Membrane+Bending (Inside)	-24924 psi
Membrane+Bending (Center)	6990.3 psi
Membrane+Bending (Outside)	38905 psi
Peak (Inside)	45661 psi
Peak (Center)	4074.1 psi
Peak (Outside)	-6148.7 psi
Total (Inside)	20737 psi
Total (Center)	11064 psi
Total (Outside)	32756 psi







Validation: 1.5” Shell Design with 3/8” Annular

Smooth Bar Fatigue

In accordance with ASME Section VIII Div II, 5.5.3.2 and 3-F.1:

- SCL 1: Top of Annular Plate at Toe of Weld
  - K_f equal to 1.7 for as-welded surface with MT/PT and VT examination per Table 5.12
- SCL 2a: Exposed Surface of Weld
  - K_f equal to 1.7 for as-welded surface with MT/PT and VT examination per Table 5.12
- SCL 2b: Unexposed Surface of Weld
  - K_f equal to 4.0 for weld backsides that receive no examination per Table 5.12
- m and n per Table 5.13 for carbon steel

	SCL 1	SCL2a	SCL2b	
Mat'l =	A537 CL2	A537 CL2 / E8018	A537 CL2 / E8018	-
S =	24	24	24	ksi
Fy =	60	60	60	ksi
Fu =	80	80	80	ksi
S_{PS} =	72	72	72	ksi
Section 5.5.3.2				
σ^e_m =	2.014	6.989	6.989	ksi
σ^e_b =	64.62	31.916	-31.914	ksi
E_T =	29000	29000	29000	ksi
ΔS_n =	66.637	38.905	24.925	ksi
ΔS_p =	66.637	38.905	24.925	ksi
m =	3.0	3.0	3.0	-
n =	0.2	0.2	0.2	-
K_e =	1	1	1	-
K_f =	1.7	1.7	4	-
S_{alt} =	56.64	33.07	49.85	ksi
Section 3-F.1				
Y =	1.743	1.509	1.687	-
10^Y =	55.274	32.271	48.647	-
Eqn 3-F.2	3.511	4.240	3.688	-
Eqn 3-F.3	3.235	4.104	3.420	-
X =	3.511	4.240	3.688	-
N =	3247	17387	4871	cycles

Validation: 1.5” Shell Design with 3/8” Annular

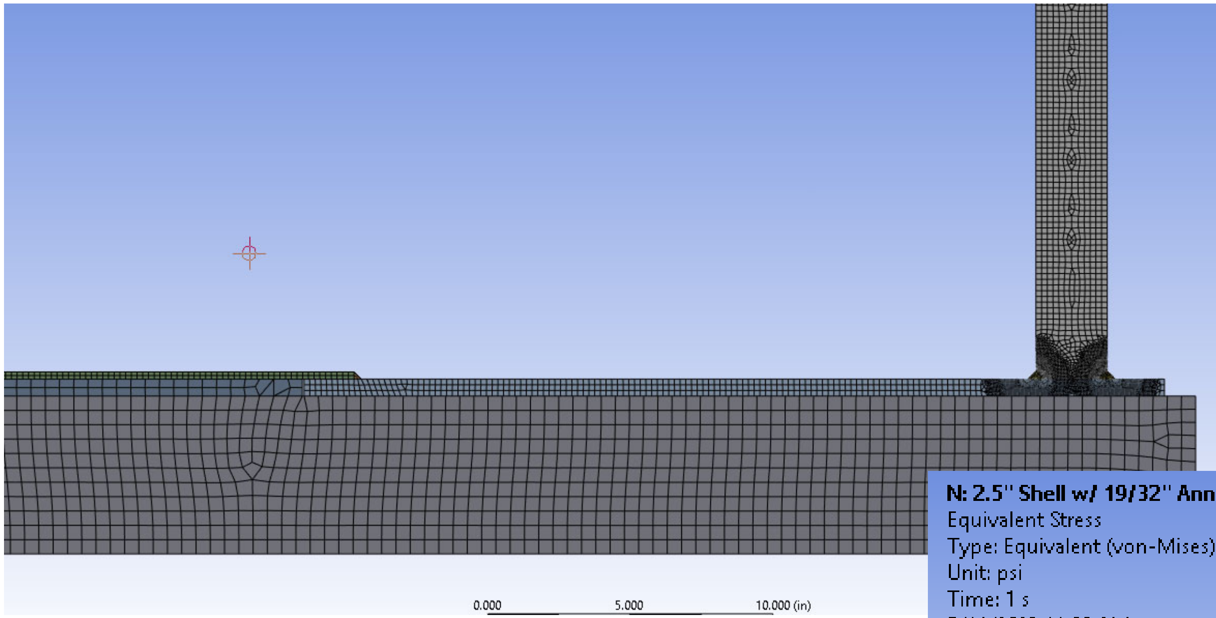
Welded Joint Fatigue

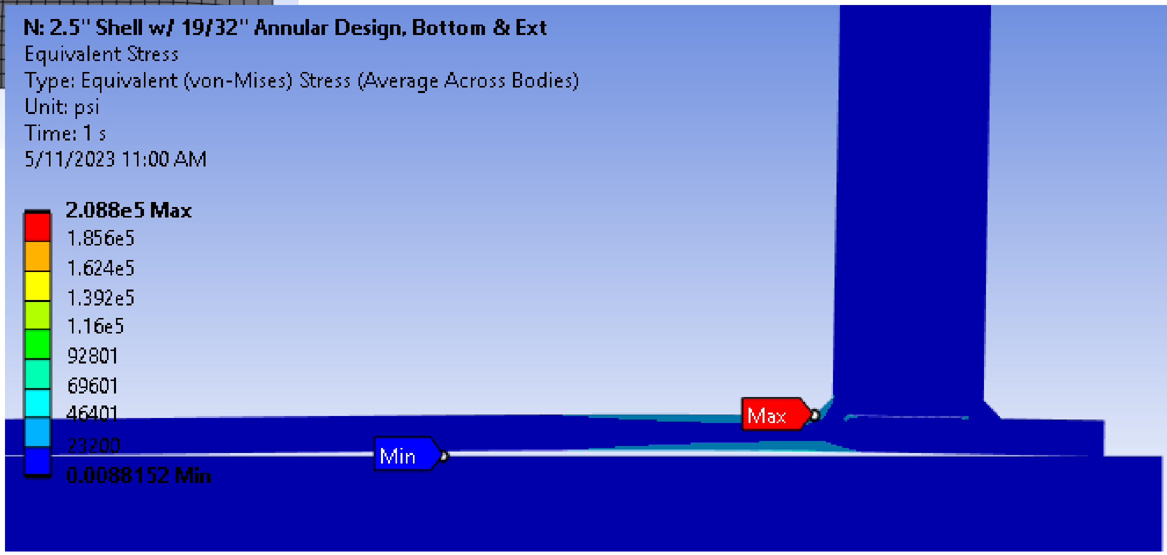
In accordance with ASME Section VIII Div II, 5.5.5.2 and 3-F.2:

- C and h per Table 3-F.2 Lower 99% Prediction Interval for Ferritic and Stainless Steels
- SCL 1: Top of Annular Plate at Toe of Weld
  - n_{CSS} and K_{CSS} per Table 3-D.2 for Carbon Steel 0.75in Base Metal
- SCL 2a: Exposed Surface of Weld
  - n_{CSS} and K_{CSS} per Table 3-D.2 for Carbon Steel 0.75in Weld Metal
- SCL 2b: Unexposed Surface of Weld
  - n_{CSS} and K_{CSS} per Table 3-D.2 for Carbon Steel 0.75in Weld Metal
- Environmental Modification Factor, f_E of 4.0 is considered as a stress concentration factor.

		SCL 1	SCL 2a	SCL 2b	
Section 5.5.5.2					
	P =	0.04099			ksi
	σ^e_m =	2.0143	6.989	6.989	ksi
	σ^e_b =	64.623	31.916	-31.914	ksi
	n_{CSS} =	0.128	0.110	0.11	-
	K_{CSS} =	109.8	100.8	100.8	-
$\Delta\sigma$	High Cycle	64.63	39.015	25.21	ksi
	Low Cycle	75.59	42.723	26.99	ksi
ΔS_{ess}	High Cycle	44.08	27.37	17.69	ksi
	Low Cycle	51.55	29.97	18.94	ksi
Section 3-F.2					
	C =	818.3			-
	h =	0.3195			-
	f_I =	1.0			-
	f_E =	4.0			-
N	High Cycle	2338	10387	40748	-
	Low Cycle	1432	7817	32903	-

Validation: 2.5” Shell Design with 19/32” Annular



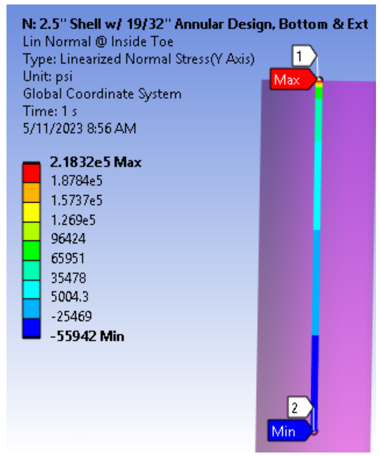


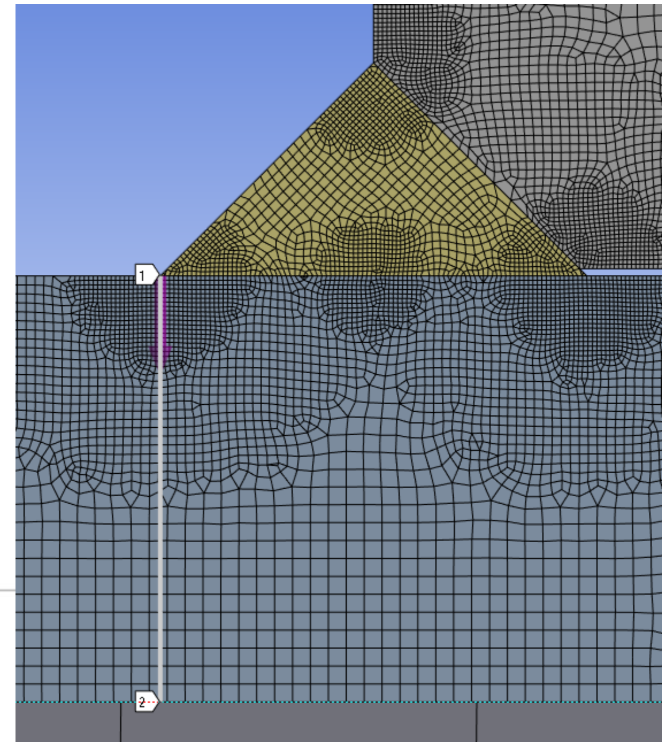
Validation: 2.5” Shell Design with 19/32” Annular

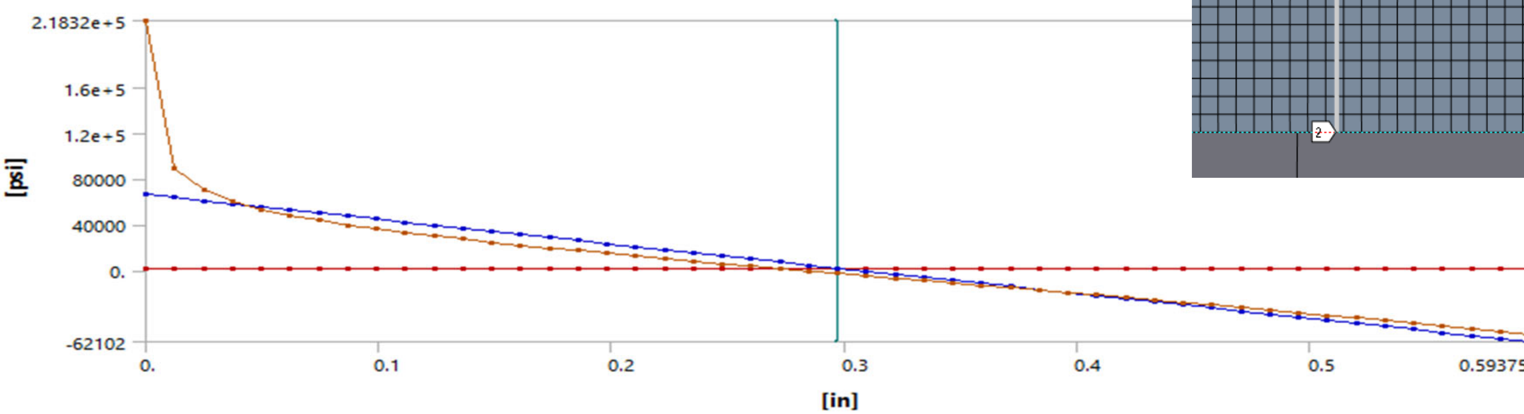
SCL 1

Results	
Membrane	2171.5 psi
Bending (Inside)	64274 psi
Bending (Outside)	-64274 psi
Membrane+Bending (Inside)	66446 psi
Membrane+Bending (Center)	2171.5 psi
Membrane+Bending (Outside)	-62102 psi
Peak (Inside)	1.5187e+005 psi
Peak (Center)	-4600.5 psi
Peak (Outside)	6160.3 psi
Total (Inside)	2.1832e+005 psi
Total (Center)	-2429. psi
Total (Outside)	-55942 psi

Information



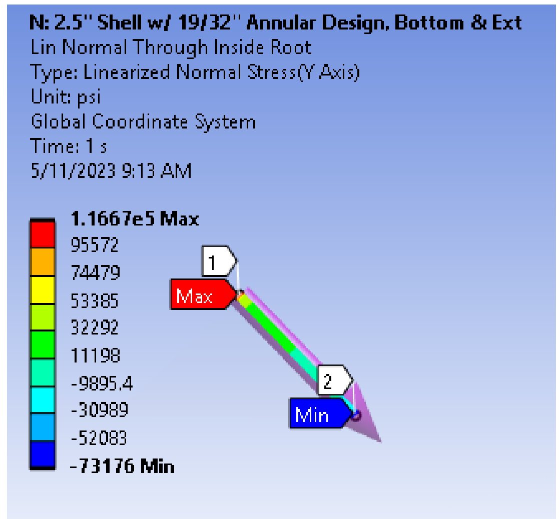


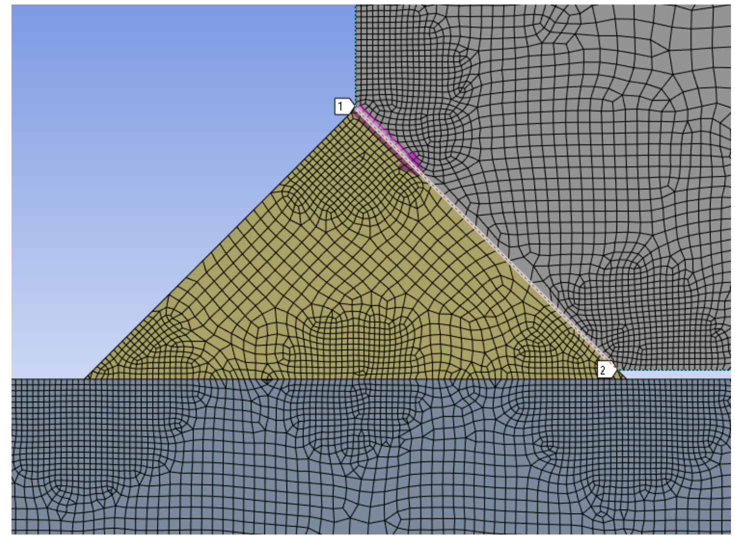


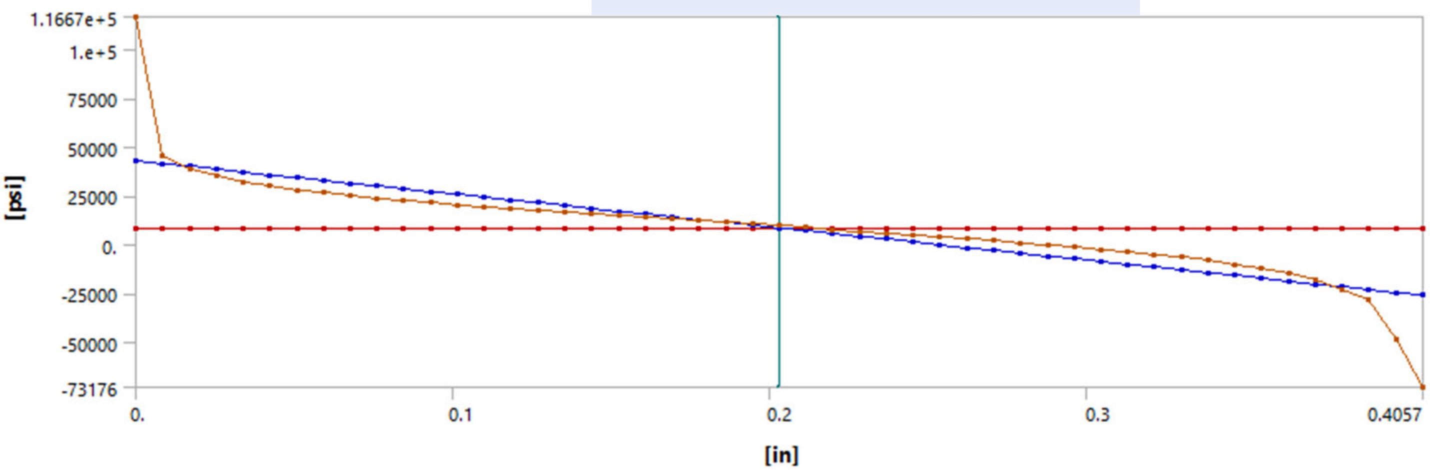
Validation: 2.5” Shell Design with 19/32” Annular

SCL 2

Results	
Membrane	8452.2 psi
Bending (Inside)	34440 psi
Bending (Outside)	-34437 psi
Membrane+Bending (Inside)	42892 psi
Membrane+Bending (Center)	8453.4 psi
Membrane+Bending (Outside)	-25985 psi
Peak (Inside)	73774 psi
Peak (Center)	1055.7 psi
Peak (Outside)	-47191 psi
Total (Inside)	1.1667e+005 psi
Total (Center)	9509.1 psi
Total (Outside)	-73176 psi







Validation: 2.5” Shell Design with 19/32” Annular

Smooth Bar Fatigue

In accordance with ASME Section VIII Div II, 5.5.3.2 and 3-F.1:

- SCL 1: Top of Annular Plate at Toe of Weld
  - K_f equal to 1.7 for as-welded surface with MT/PT and VT examination per Table 5.12
- SCL 2a: Exposed Surface of Weld
  - K_f equal to 1.7 for as-welded surface with MT/PT and VT examination per Table 5.12
- SCL 2b: Unexposed Surface of Weld
  - K_f equal to 4.0 for weld backsides that receive no examination per Table 5.12
- m and n per Table 5.13 for carbon steel

	SCL 1	SCL2a	SCL2b	
Mat'l =	A537 CL2	A537 CL2 / E8018	A537 CL2 / E8018	-
S =	24	24	24	ksi
Fy =	60	60	60	ksi
Fu =	80	80	80	ksi
S_{PS} =	72	72	72	ksi
Section 5.5.3.2				
σ^e_m =	2.1715	8.4522	8.649	ksi
σ^e_b =	64.274	34.44	-34.437	ksi
E_T =	29000	29000	29000	ksi
ΔS_n =	66.446	42.892	25.788	ksi
ΔS_p =	66.446	42.892	25.788	ksi
m =	3.0	3.0	3.0	-
n =	0.2	0.2	0.2	-
K_e =	1	1	1	-
K_f =	1.7	1.7	4	-
S_{alt} =	56.48	36.46	51.58	ksi
Section 3-F.1				
Y =	1.741	1.551	1.702	-
10^Y =	55.115	35.578	50.331	-
Eqn 3-F.2	3.515	4.113	3.641	-
Eqn 3-F.3	3.239	3.929	3.369	-
X =	3.515	4.113	3.641	-
N =	3276	12982	4370	cycles

Validation: 2.5" Shell Design with 19/32" Annular

Welded Joint Fatigue

In accordance with ASME Section VIII Div II, 5.5.5.2 and 3-F.2:

- C and h per Table 3-F.2 Lower 99% Prediction Interval for Ferritic and Stainless Steels
- SCL 1: Top of Annular Plate at Toe of Weld
  - n_{CSS} and K_{CSS} per Table 3-D.2 for Carbon Steel 0.75in Base Metal
- SCL 2a: Exposed Surface of Weld
  - n_{CSS} and K_{CSS} per Table 3-D.2 for Carbon Steel 0.75in Weld Metal
- SCL 2b: Unexposed Surface of Weld
  - n_{CSS} and K_{CSS} per Table 3-D.2 for Carbon Steel 0.75in Weld Metal
- Environmental Modification Factor, f_E of 4.0 is considered as a stress concentration factor.

		SCL 1	SCL 2a	SCL 2b	
Section 5.5.5.2					
	P =	0.041667			ksi
	σem =	2.1715	8.4522	8.4522	ksi
	σeb =	64.274	34.44	-34.44	ksi
	n_{CSS} =	0.128	0.110	0.110	-
	K_{CSS} =	109.8	100.8	100.8	-
Δσ	High Cycle	64.49	42.93	25.99	ksi
	Low Cycle	75.33	47.18	28.46	ksi
ΔS_{ess}	High Cycle	44.00	30.20	18.28	ksi
	Low Cycle	51.40	33.19	20.02	ksi
Section 3-F.2					
	C =	818.3			-
	h =	0.3195			-
	f_I =	1.0			-
	f_E =	4.0			-
N	High Cycle	2350	7637	36754	-
	Low Cycle	1445	5682	27648	-

Validation: Summary of Results

- The resulting number of cycles consistently exceed the stated 1300 cycles.
- The limiting number of cycles is consistently shown to be through the annular plate (SCL 1) using the low cycle equivalent structural stress determined with the Welded Joint Fatigue approach. However, considering that the factors used for the WJF procedure are not developed for the temperatures or thicknesses consistent with this evaluation, the smooth bar approach may be the mor reliable result.
- Both validation examples have similar number of cycles through the annular plate.

1.5" Shell Design with 3/8" Annular									
	Through Annular Plate			**Through Weld**					
				Exposed			Unexposed		
	Welded Joint		Smooth	Welded Joint		Smooth	Welded Joint		Smooth
	High	Low	Bar	High	Low	Bar	High	Low	Bar
Cycles	2338	1432	3247	10387	7817	17387	40748	32903	4871

2.5" Shell Design with 19/32" Annular									
	Through Annular Plate			**Through Weld**					
				Exposed			Unexposed		
	Welded Joint		Smooth	Welded Joint		Smooth	Welded Joint		Smooth
	High	Low	Bar	High	Low	Bar	High	Low	Bar
Cycles	2350	1445	3276	7637	5682	12982	36754	27648	4370

Conclusions

The proposed table in agenda item 620-1024 seems acceptable based on the validation of the two example shell designs presented in this document.

Thickness	20 000	22 000	24 000	26 000
0.75`	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$
1.`	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{5}{16}$
1.25`	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{5}{16}$	$\frac{3}{8}$
1.5`	$\frac{1}{4}$	$\frac{9}{32}$	$\frac{3}{8}$	$\frac{7}{16}$
1.75`	$\frac{1}{4}$	$\frac{5}{16}$	$\frac{7}{16}$	$\frac{17}{32}$
2.`	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{15}{32}$	$\frac{19}{32}$
2.25`	$\frac{9}{32}$	$\frac{13}{32}$	$\frac{17}{32}$	$\frac{11}{16}$
2.5`	$\frac{5}{16}$	$\frac{7}{16}$	$\frac{19}{32}$	$\frac{3}{4}$

Future Considerations….

A similar approach may be used in the future for other updates that may want to be considered:

- USC in Decimal format instead of Fractional
- A table for SI when metrification is complete
- Additional tables if there’s a need to include thicknesses for cycles greater than 1300
  - Or provide rules or guidance for determining the number of cycles

Supplemental Runs

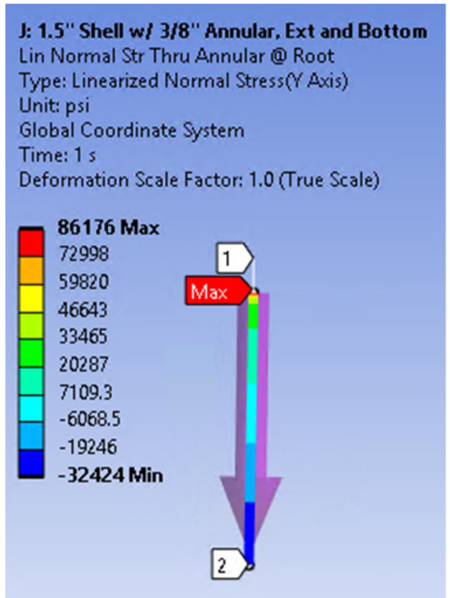
- Additional scenarios were considered in response to the RTTG comment only ballot

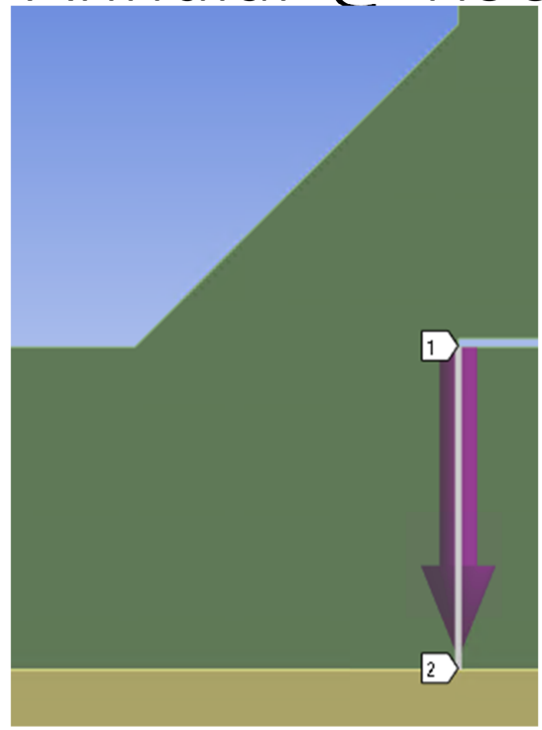
  - For the 1.5” shell case, a vertical SCL through the annular plate where the root of the inside fillet weld intersects the annular plate

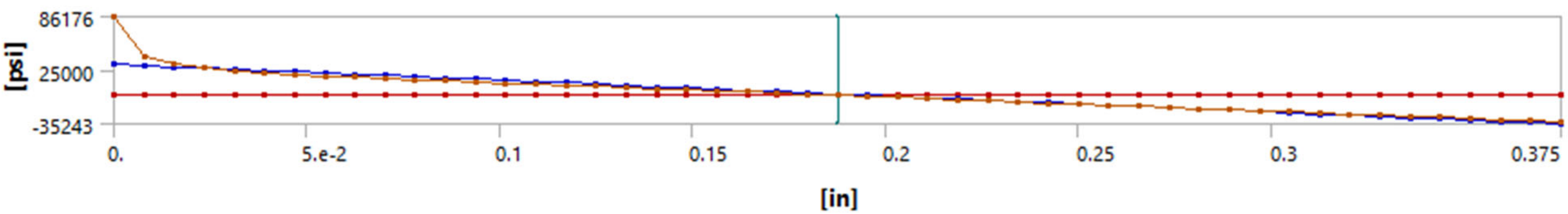
  - Check the stresses and number of cycles for 1.5” and 2.5” shell case with a frictional contact between bottom/annular and the concrete course.

Supplemental Runs: SCL Through Annular @ Root

Results	
Membrane	-1535.9 psi
Bending (Inside)	33707 psi
Bending (Outside)	-33707 psi
Membrane+Bending (Inside)	32171 psi
Membrane+Bending (Center)	-1535.9 psi
Membrane+Bending (Outside)	-35243 psi
Peak (Inside)	54005 psi
Peak (Center)	-1314.9 psi
Peak (Outside)	2818.5 psi
Total (Inside)	86176 psi
Total (Center)	-2850.8 psi
Total (Outside)	-32424 psi







Supplemental Runs: SCL Through Annular @ Root

- SCL 1: Top of Annular Plate at Toe of Weld
  - From Initial Effort for Reference
- SCL 1b: Through Annular Plate at Root of Fillet Weld
  - Provided in Response to Comments
- The smooth bar fatigue approach shows one third reduction of the number of cycles while the Weld Joint Fatigue shows this a significant increase in the number of cycles.
- This SCL does not seem to be a typical SCL that's evaluated.
- For the smooth bar approach, a K_f=4 is a conservative value. Stresses parallel to a notch wouldn't typically have that large of a stress amplification.
- All results exceed 1300 cycles.

Smooth Bar			
	SCL 1	SCL 1b	
Mat'l =	A537 CL2	A537 CL2	-
S =	24	24	ksi
Fy =	60	60	ksi
Fu =	80	80	ksi
S_{PS} =	72	72	ksi
Section 5.5.3.2			
$\sigma^e{}_m$ =	2.014	-1.536	ksi
$\sigma^e{}_b$ =	64.62	33.707	ksi
E_T =	29000	29000	ksi
ΔS_n =	66.637	32.171	ksi
ΔS_p =	66.637	32.171	ksi
m =	3.0	3.0	-
n =	0.2	0.2	-
K_e =	1	1	-
K_f =	1.7	4	-
S_{alt} =	56.64	64.34	ksi
Section 3-F.1			
Y =	1.743	1.798	-
10^Y =	55.274	62.789	-
Eqn 3-F.2	3.511	3.339	-
Eqn 3-F.3	3.235	3.064	-
X =	3.511	3.339	-
N =	3247	2182	cycles

Weld Joint Fatigue				
		SCL 1	**SCL1b**	
Section 5.5.5.2				
	P =	0.04099		ksi
	$\sigma^e{}_m$ =	2.0143	-1.536	ksi
	$\sigma^e{}_b$ =	64.623	33.707	ksi
	n_{CSS} =	0.128	0.128	-
	K_{CSS} =	109.8	109.8	-
$\Delta\sigma$	High Cycle	64.63	32.20	ksi
	Low Cycle	75.59	35.41	ksi
ΔS_{ess}	High Cycle	44.08	22.02	ksi
	Low Cycle	51.55	24.21	ksi
Section 3-F.2				
	C =	818.3		-
	h =	0.3195		-
	f_I =	1.0		-
	f_E =	4.0		-
N	High Cycle	2338	20515	-
	Low Cycle	1432	15247	-

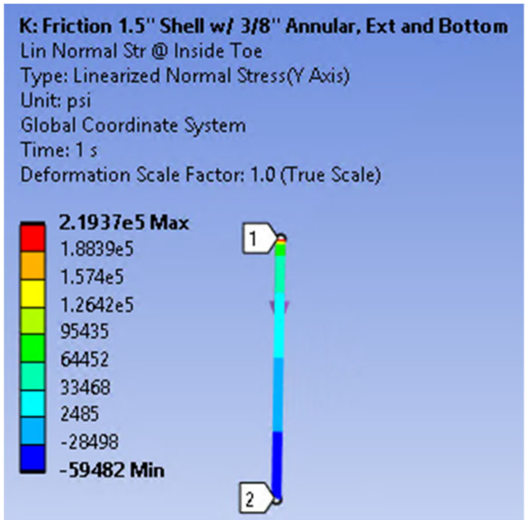
Supplemental Runs: Frictional Contact

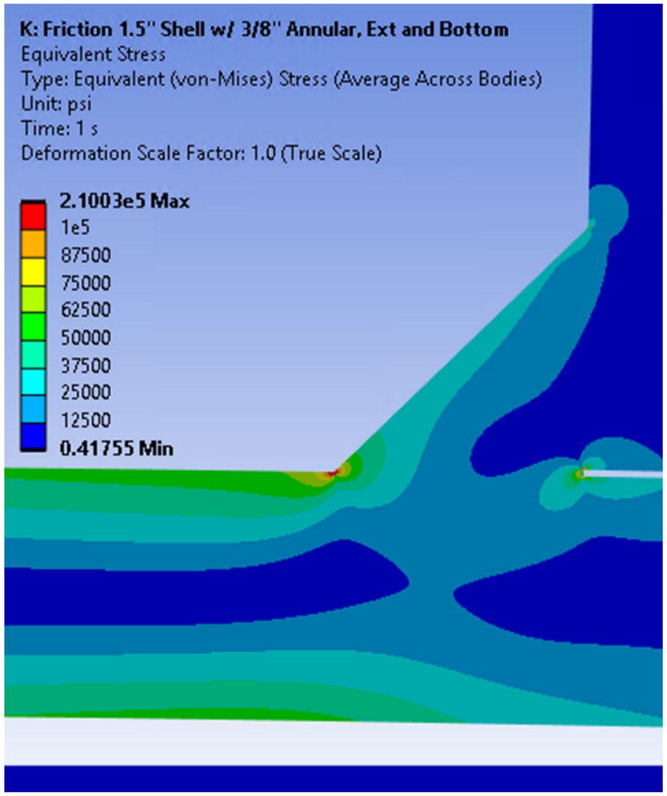
- Only results for SCL 1 (Through Annular at Inside Toe of Weld) will be reported since that was previously shown as the limiting SCL.
- A friction coefficient of 0.577 is considered. This is a conservative friction factor that is taken from API 620 Annex L for the SSE sliding resistance check.

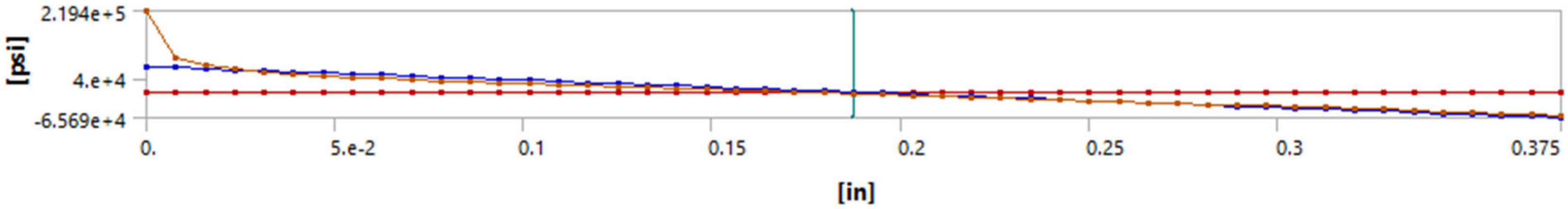
Supplemental Runs: Frictional Contact

SCL 1f for 1.5” Shell w/ 3/8” Annular

Membrane	2467.7 psi
Bending (Inside)	68154 psi
Bending (Outside)	-68154 psi
Membrane+Bending (Inside)	70622 psi
Membrane+Bending (Center)	2467.7 psi
Membrane+Bending (Outside)	-65687 psi
Peak (Inside)	1.4875e+005 psi
Peak (Center)	-4655.3 psi
Peak (Outside)	6204.7 psi
Total (Inside)	2.1937e+005 psi
Total (Center)	-2187.7 psi
Total (Outside)	-59482 psi





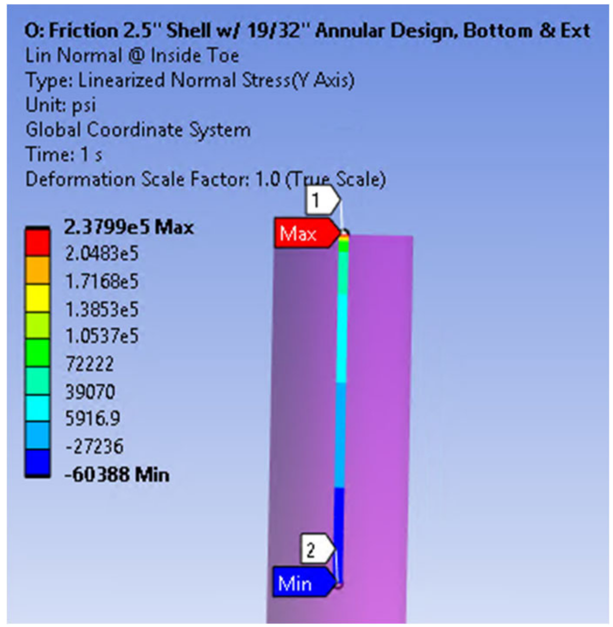


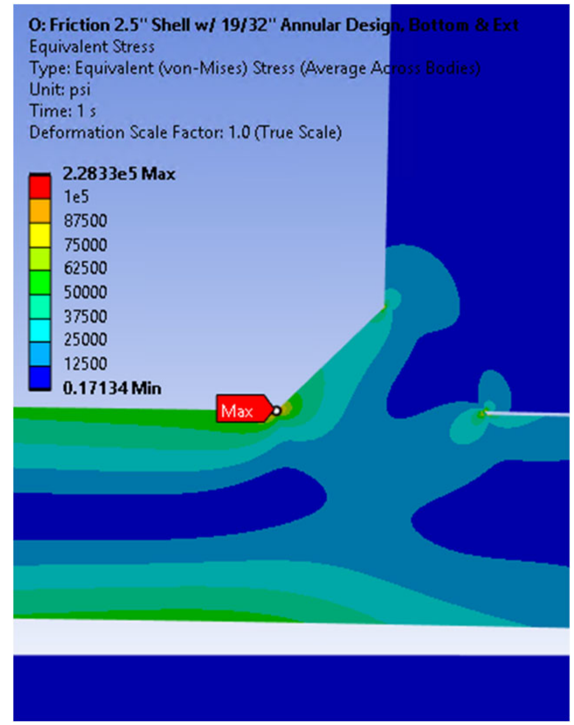
Supplemental Runs: Frictional Contact

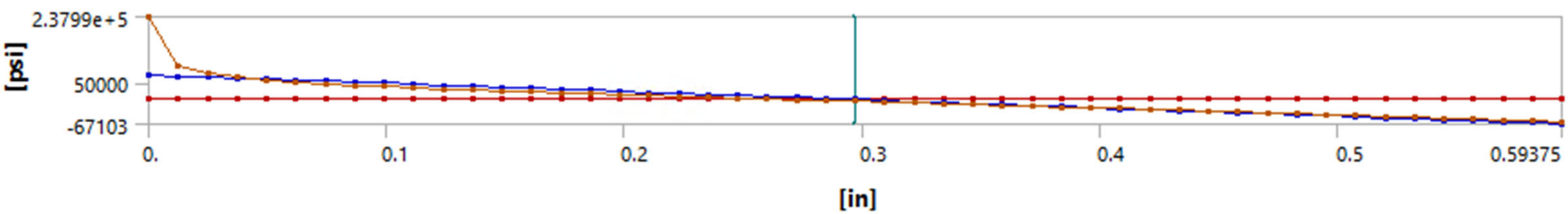
SCL 1f for 2.5” Shell w/ 19/32” Annular

Results	
Membrane	2711.7 psi
Bending (Inside)	69814 psi
Bending (Outside)	-69814 psi
Membrane+Bending (Inside)	72526 psi
Membrane+Bending (Center)	2711.7 psi
Membrane+Bending (Outside)	-67103 psi
Peak (Inside)	1.6546e+005 psi
Peak (Center)	-5008. psi
Peak (Outside)	6714.2 psi
Total (Inside)	2.3799e+005 psi
Total (Center)	-2296.3 psi
Total (Outside)	-60388 psi

Information







Supplemental Runs: Frictional Contact

- SCL 1: Top of Annular Plate at Toe of Weld From Initial Effort for Reference
- SCL 1f: Same SCL as above with the Frictional Contact
- Both Smooth Bar and Weld Joint Fatigue approaches show a reduction in number of cycles when frictional contact is considered
- Smooth Bar still shows greater than 1300 cycles.
- Low Cycle WJF shows less than 1300.

Smooth Bar					
	1.5" Shell 3/8" Annular		2.5" Shell 19/32" Annular		
	SCL 1	**SCL1f**	**SCL 1**	**SCL1f**	
Section 5.5.3.2					
σ^e_m =	2.014	2.468	2.172	2.712	ksi
σ^e_b =	64.62	68.15	64.274	69.814	ksi
E_T =	29000				ksi
ΔS_n =	66.637	70.622	66.446	72.526	ksi
ΔS_p =	66.637	70.622	66.446	72.526	ksi
m =	3.0				-
n =	0.2				-
K_e =	1				-
K_f =	1.7				-
S_{alt} =	56.64	60.03	56.48	61.65	ksi
Section 3-F.1					
Y =	1.743	1.768	1.741	1.779	-
10^Y =	55.274	58.57973	55.115	60.159	-
Eqn 3-F.2	3.511	3.432	3.515	3.396	-
Eqn 3-F.3	3.235	3.156	3.239	3.120	-
X =	3.511	3.432	3.515	3.396	-
N =	3247	2705	3276	2490	cycles

Weld Joint Fatigue						
		1.5" Shell 3/8" Annular		2.5" Shell 19/32" Annular		
		SCL 1	**SCL1f**	**SCL 1**	**SCL1f**	
Section 5.5.5.2						
	P =	0.04099		0.04167		ksi
	σ^e_m =	2.0143	2.468	2.1715	2.712	ksi
	σ^e_b =	64.623	68.154	64.274	69.814	ksi
	n_{CSS} =	0.128				-
	K_{CSS} =	109.8				-
$\Delta\sigma$	High Cycle	64.63	67.76	64.49	69.16	ksi
	Low Cycle	75.59	80.98	75.33	83.67	ksi
ΔS_{ess}	High Cycle	44.08	46.26	44.00	47.25	ksi
	Low Cycle	51.55	55.29	51.40	57.16	ksi
Section 3-F.2						
	C =	818.3				-
	h =	0.3195				-
	f_I =	1.0				-
	f_E =	4.0				-
N	High Cycle	2338	2010	2350	1881	-
	Low Cycle	1432	1150	1445	1037	-

Supplemental Runs: Conclusion

- Despite some of the number of cycles with the frictional contact runs being less than 1300 cycles, it is still reasonable to proceed with the proposed agenda item.
- Important to consider a few things:
  - The FEA examples are provided for information only as a reference since the basis of the Table R-6 extrapolation to thicker shell plates is using the original methodology.
  - Weld Joint Fatigue approach is not directly applicable to this scenario since the factors are correlated with ambient temperatures and provide coefficients for a minimum weld metal thickness of 0.75” while the modeled welds are limited to 0.5” per API 620. It is only for the upper bound of the annular plate thicknesses from Table R-6 that are near the coefficients provided for 0.75” base metal thickness.
  - Smooth bar approach is more consistent with the original basis which reported greater than 1300 cycles for all scenarios.
  - The friction coefficient used in the supplemental analysis is conservative, so the true impact of friction applied to the model would be somewhere in the middle ground.