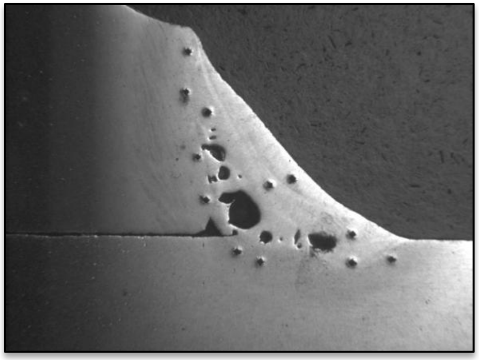
Twin Cities
ANSYS® User Meeting

August 2012

Weld Analysis



... within Epsilon

Agenda

1. Explicitly Modeled Welds
2. Extracting Stresses for Hand-Calculations
   - Path Operations
   - Stress Linearization
3. Designing / Lifing Welds - -Chris Wright P.E.

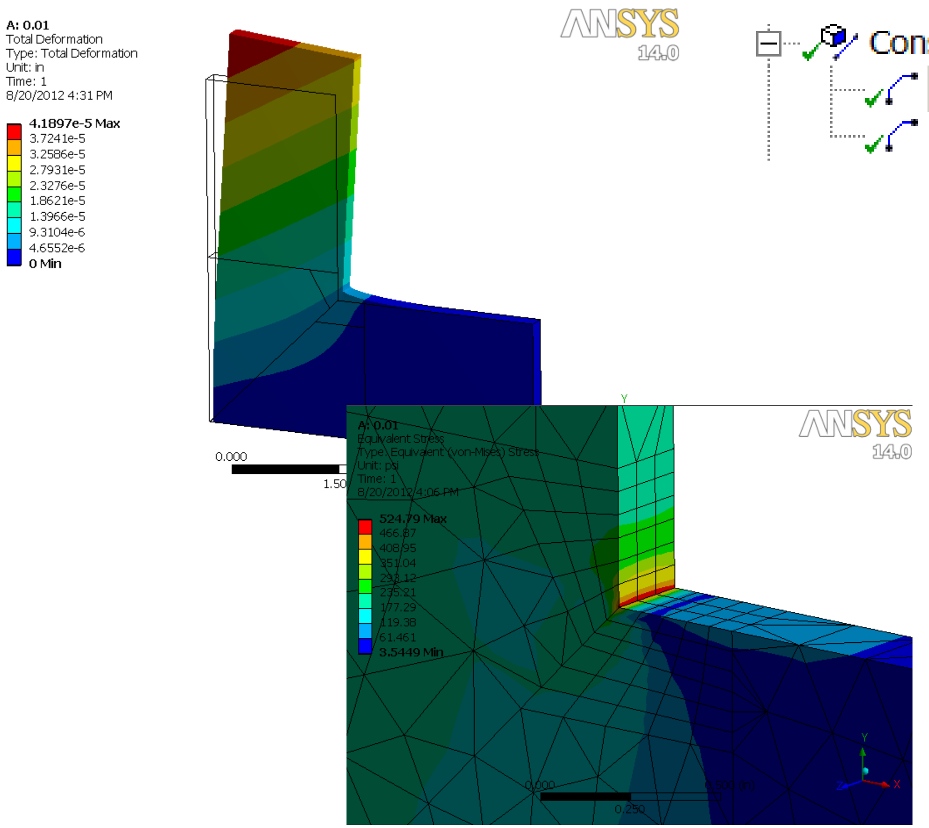
Explicitly Modeled Welds

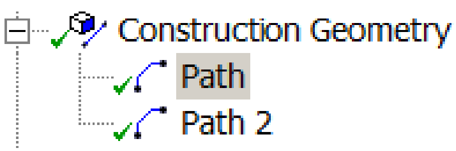
… within Epsilon

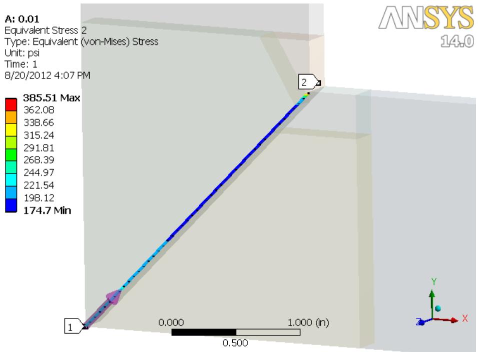
1. Material Properties are undefined
   - Heat affected zone
     - Composition varies spatially due to material mixing/cooling rates
     - Would need fatigue properties gathered at various R-ratios and compositions?
     - Welding/Cooling rates depend on weld process/operator
2. Geometric Variations also hard to assess
3. Process would be similar to Soldering/Semiconductor
   1. Model weld bead explicitly
   2. Use viscoplastic material model (e.g. Anands)
   3. Have modulus approach zero above weld temperature
   4. Use Element Birth/Death to “activate” along the weld line
   5. Use Heat Generation along weld as elements are activated
   6. Cool with HTC’s for quiescent air… 5 btu/ft^2/sec-F?
4. Bound problem to assess (large) variation!

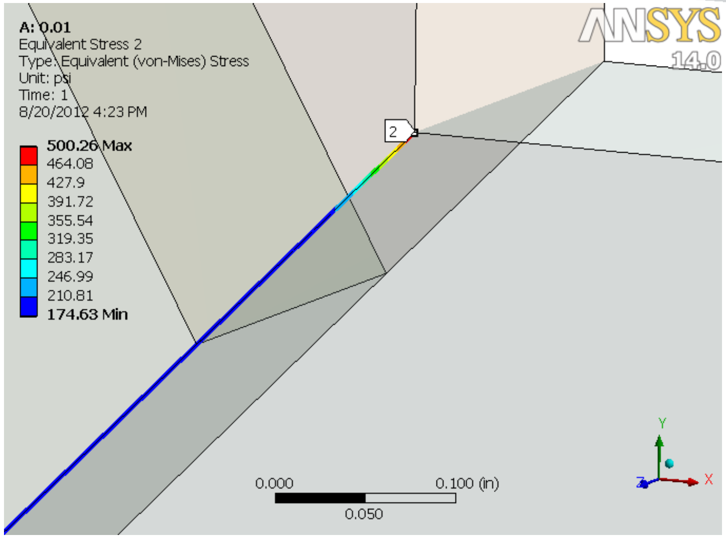
Extracting Stress Data

1. Path Operations, extracts stresses along specified path.
   - In classic steps are to define a path, and then map a result onto the path, then finally plot/list the results.





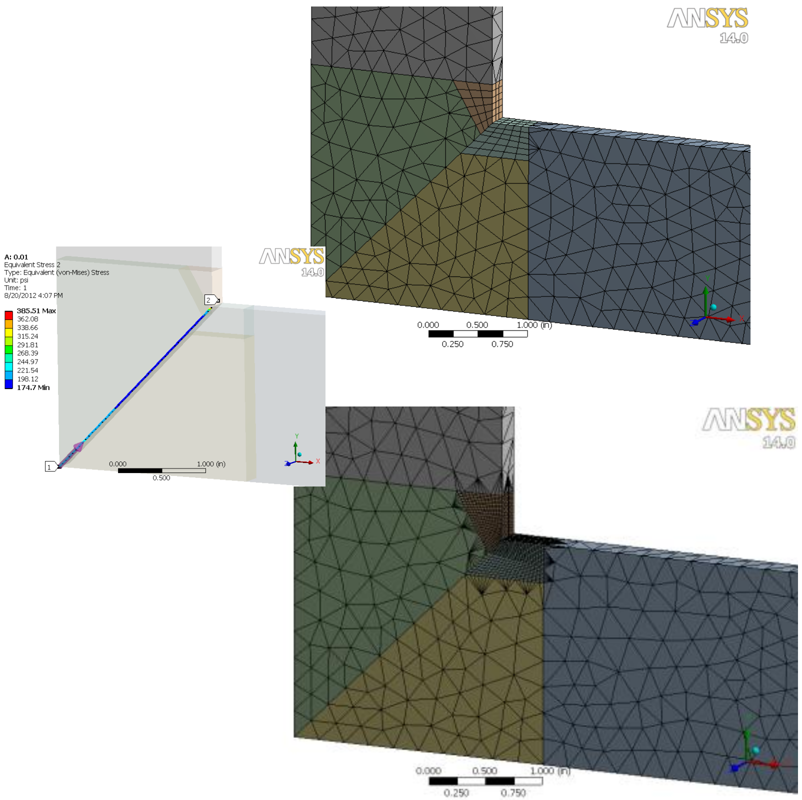


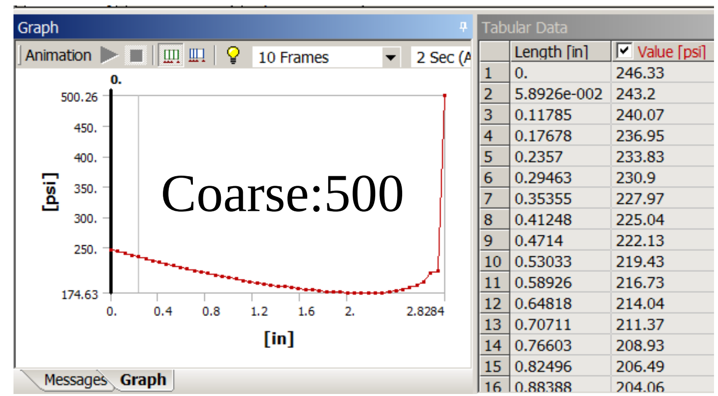


... within Epsilon

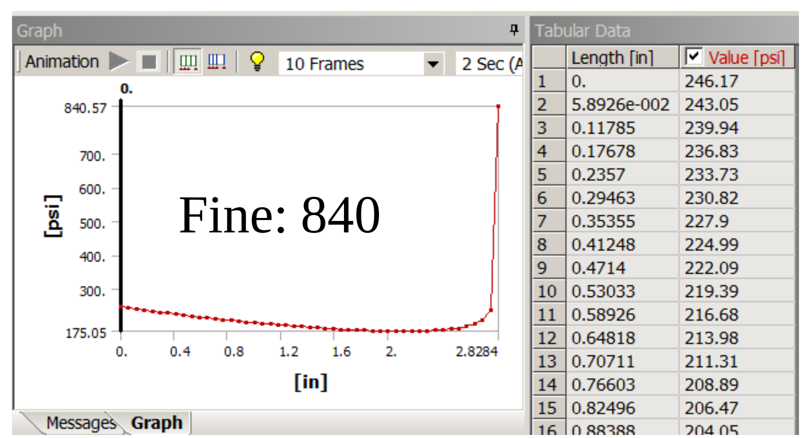
Extracting Stress Data

1. Path Operations, extracts stresses along specified path.
   - In classic steps are to define a path, and then map a result onto the path, then finally plot/list the results.
   - Highly Dependent on Mesh, and selection of points!





	Length [in]	Value [psi]
1	0.	246.33
2	5.8926e-002	243.2
3	0.11785	240.07
4	0.17678	236.95
5	0.2357	233.83
6	0.29463	230.9
7	0.35355	227.97
8	0.41248	225.04
9	0.4714	222.13
10	0.53033	219.43
11	0.58926	216.73
12	0.64818	214.04
13	0.70711	211.37
14	0.76603	208.93
15	0.82496	206.49
16	0.88388	204.06

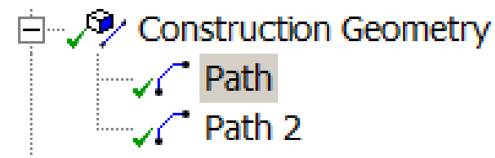


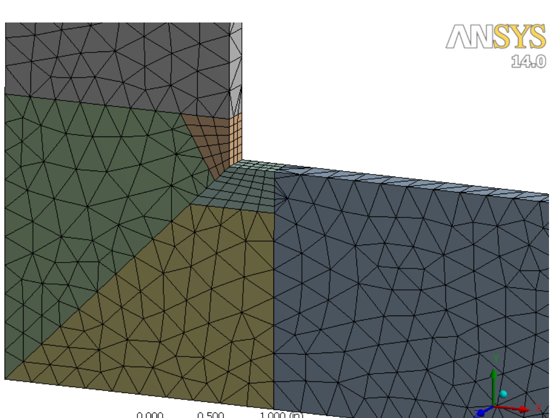
	Length [in]	Value [psi]
1	0.	246.17
2	5.8926e-002	243.05
3	0.11785	239.94
4	0.17678	236.83
5	0.2357	233.73
6	0.29463	230.82
7	0.35355	227.9
8	0.41248	224.99
9	0.4714	222.09
10	0.53033	219.39
11	0.58926	216.68
12	0.64818	213.98
13	0.70711	211.31
14	0.76603	208.89
15	0.82496	206.47
16	0.88388	204.05

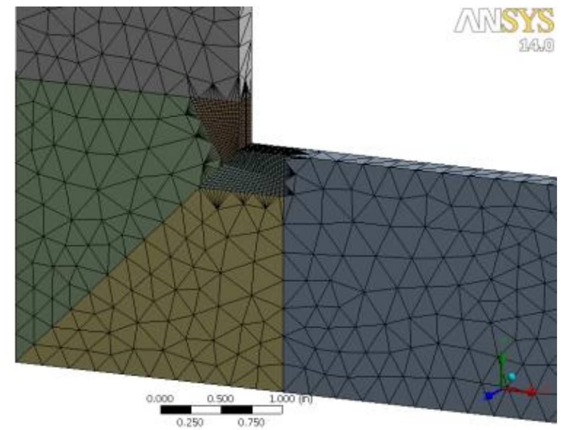
Extracting Stress Data

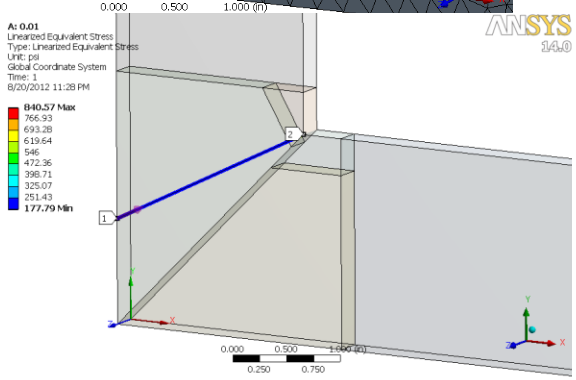
1. Path Operations, **Stress Linearization**

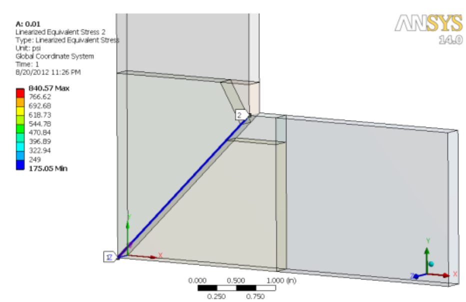
- Relatively sensitive to Mesh, and selection of points!
- Will match hand-calc's with no KT's applied (in theory)
- Devolves stress into tensile and bending components!











Extracting Stress Data

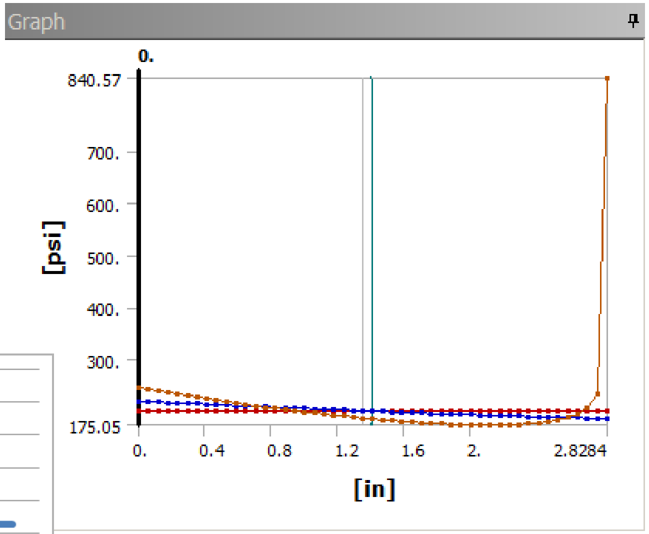
... within Epsilon

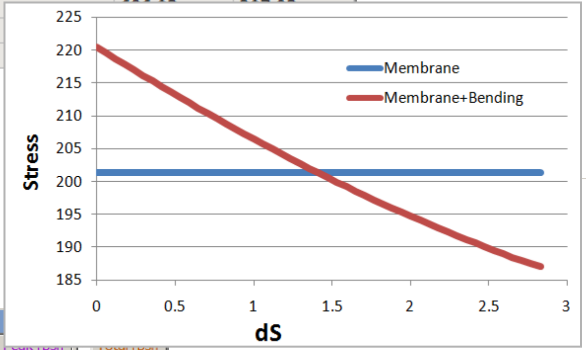
1. Path Operations, **Stress Linearization**

Tabular Data

	Length [in]	Membrane [psi]	Bending [psi]	Membrane+Bending [psi]	Peak [psi]	Total [psi]
39	2.2392	201.31	20.848	192.29	572.23	175.57
40	2.2981	201.31	22.337	191.72	586.45	175.85
41	2.357	201.31	23.826	191.16	600.68	176.89
42	2.4159	201.31	25.315	190.61	614.9	178.49
43	2.4749	201.31	26.804	190.06	629.13	180.53
44	2.5338	201.31	28.293	189.53	643.35	183.04
45	2.5927	201.31	29.782	189.01	657.58	188.59
46	2.6517	201.31	31.272	188.49	671.8	195.48
47	2.7106	201.31	32.761	187.99	[illegible]	[illegible]
48	2.7695	201.31	34.25	[illegible]	[illegible]	[illegible]
49	2.8284	201.31	35.739	187.02	[illegible]	[illegible]

Fine: 187





Coarse: 188

Tabular Data

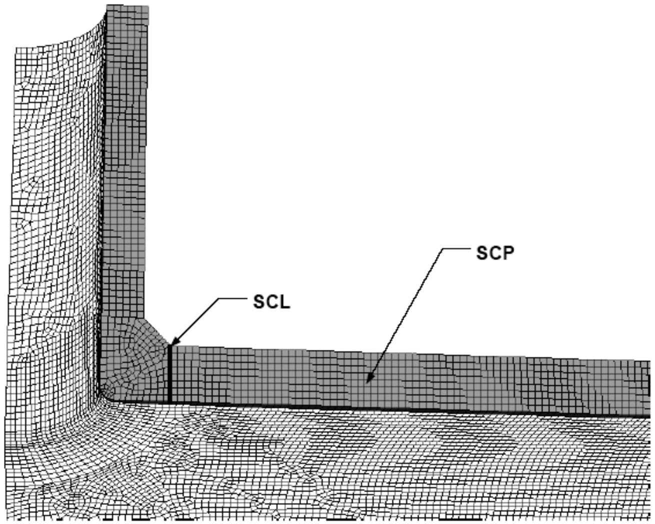
	Length [in]	Membrane [psi]	Bending [psi]	Membrane+Bending [psi]	Peak [psi]	Total [psi]
39	1.7702	200.95	19.176	192.53	576.84	178.27
40	1.8168	200.95	20.546	191.99	591.12	178.03
41	1.8634	200.95	21.915	191.46	605.4	177.79
42	1.91	200.95	23.285	190.93	619.68	179.13
43	1.9566	200.95	24.655	190.41	633.96	181.2
44	2.0031	200.95	26.025	189.91	648.24	183.32
45	2.0497	200.95	27.394	189.41	662.52	184.82
46	2.0963	200.95	28.764	188.91	676.8	188.57
47	2.1429	200.95	30.134	188.43	691.08	197.3
48	2.1895	200.95	31.503	[illegible]	705.36	218.61
49	2.2361	200.95	32.873	187.49	719.64	840.57

Fine / Path 2: 187

Tabular Data

	Length [in]	Membrane [psi]	Bending [psi]	Membrane+Bending [psi]	Peak [psi]	Total [psi]
32	1.8267	198.98	8.81	191.98	256.36	177.14
33	1.8856	198.98	10.069	191.	263.92	176.24
34	1.9445	198.98	11.327	190.01	271.48	175.76
35	2.0035	198.98	12.586	[illegible]	279.04	175.29
36	2.0624	198.98	13.844	188.05	286.6	174.83

ANSYS and Weld Design



Twin Cities ANSYS User Group
August 22, 2012

Design Problem

DESIGN FUNCTIONS

- Connection (not weld) design
  - Load transfer
  - Load path definition
- Determine loading
  - Magnitude
  - Distribution
- Fabrication decisions
  - Weld type
  - Geometry constraints
  - Process variables
  - Quality assurance
- Criteria
  - Working stress
  - Fatigue Assessment

CONSTRAINTS

- Design code
  - Prescriptive requirements
  - Allowable stress
  - Methodology
- Fabrication
- Material weldability
  - Set up and tooling
  - Thermal effects
- Labor intensive
  - Process qualifications
  - Welder skills
- Quality Assurance
  - Customer requirements
  - Code requirements

Modeling Problem

PARAMETERS

- Weld size
- Type
- Extent

BEHAVIOR

- Static strength
- Fatigue response
- Thermal response

CONVENTIONAL DESIGN

- Weld load carried by shear across throat
- Direct loads distributed uniformly
- Moment reactions vary radially

CRITERIA

- 0.3Fu (AISC)
- 0.6S for groove weld shear (ASME)
- 0.49S for fillet weld shear (ASME)
- Separate fatigue assessment

IMPLICIT WELD MODEL

Weld joint defined by coupling or constraints

- Weld loading developed by equilibrium and continuity
- Nodal forces define connection load distribution
- Apply design code requirements

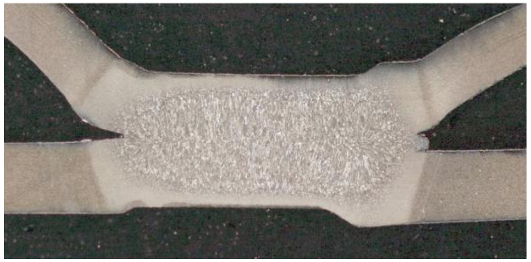
EXPLICIT WELD MODEL

- Weld contour defined in nodal mesh
- Peak stress calculated by path operation

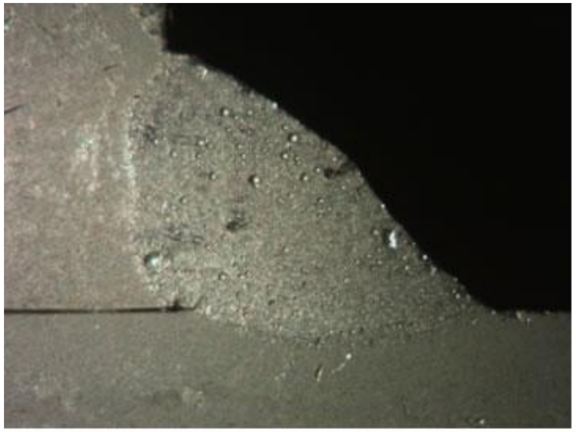
TRADE-OFFS

Implicit	Explicit
Weld size determined by from results	Weld design required beforehand
Real world features implied by Code	Weld contours and metallurgy idealized
Mesh refinement not required	Refined mesh required
No remesh required to vary weld size or type	Weld redesign requires re-model

Weld Fabrication



Spot weld



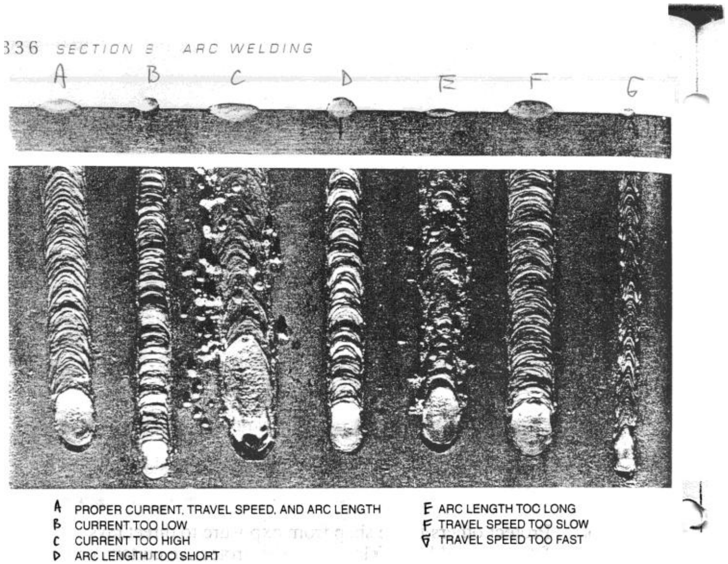
Fillet weld with porosity

Stiffener weld

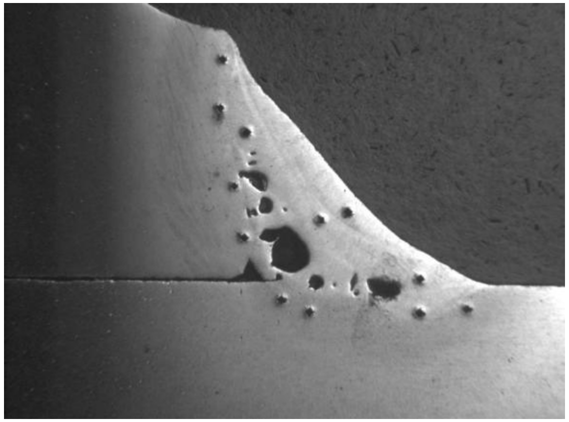
Fillet weld

Flare bevel

Quality Issues



Procedural errors

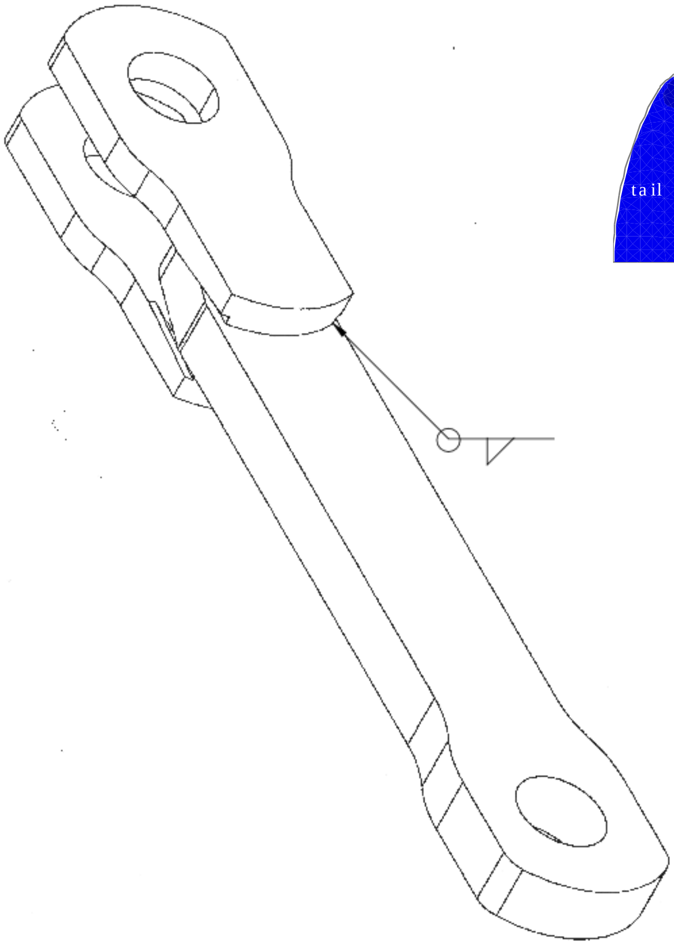


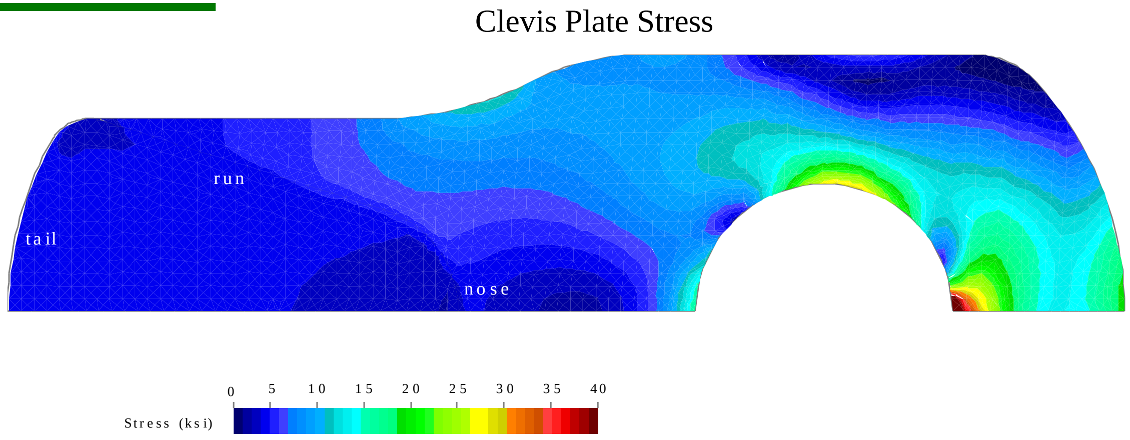
Porosity and root opening

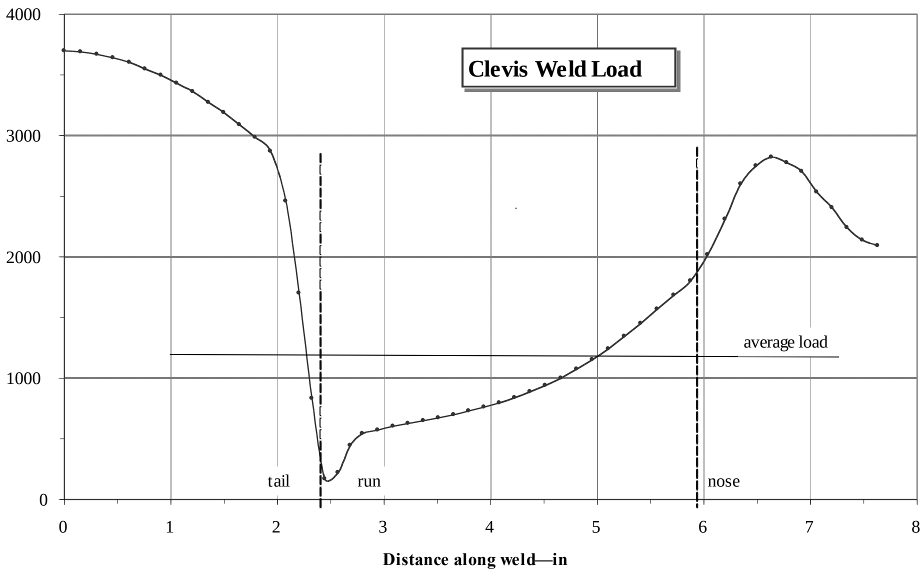
Start and stop craters

Undercut

Chain Link

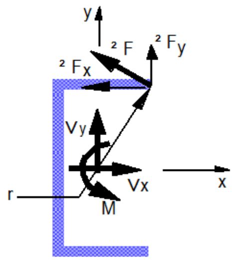



Clevis Plate Stress
run
tail
nose
Stress (ksi)
0
5
10
15
20
25
30
35
40


Clevis Weld Load
4000
3000
2000
1000
0
0
1
2
3
4
5
6
7
8
average load
tail
run
nose
Distance along weld—in

AISC/AWS Weld Design

Elastic Method



Moment Loading —

$$M = \; r_j {}^2F_j = {}^2F \quad r_j \frac{{}^2F_j}{{}^2F} = {}^2F \quad r_j \frac{r_j^2}{r}$$

$$\frac{{}^2F}{{}^2L} = Q_M = \frac{Mr}{r_j^{2}{}^2L} = t_w \frac{Mr}{J}$$

$$Q_{Mx} = t_w \frac{Mx}{J} \qquad Q_{My} = t_w \frac{My}{J}$$

Direct Loading —

$$Q_{Vx} = \frac{V_x}{L_w} \qquad Q_{Vy} = \frac{V_y}{L_w}$$

Vector sum of unit weld loads -

$$Q = \sqrt{Q_x^2 + Q_y^2} = t_w \sqrt{\left[\frac{V_x}{t_w L_w} + \frac{My}{J}\right]^2 + \left[\frac{V_y}{t_w L_w} + \frac{Mx}{J}\right]^2}$$

Eccentric Loads on Weld Groups –AISC Manual 8th edition elastic method

Normalize weld geometry to the weld group depth, l —

$J = \beta l^3 t_w$ Weld Area $= \alpha l t_w$

Assume —

$V_x = 0;\ V_y = P;\ M = \gamma P l$

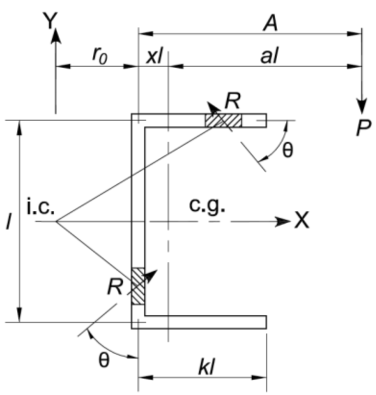
$$Q = t_w \sqrt{\left[\frac{\gamma P l y}{\beta l^3 t_w}\right]^2 + \left[\frac{P}{\alpha l t_w} + \frac{\gamma P l x}{\beta l^3 t_w}\right]^2} = \frac{P}{l}\sqrt{\left[\frac{\gamma y}{\beta l}\right]^2 + \left[\frac{1}{\alpha} + \frac{\gamma x}{\beta l}\right]^2}$$

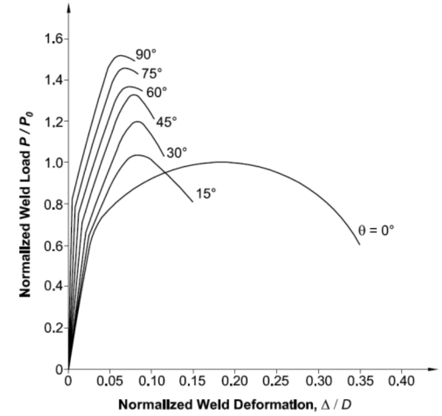
$$\text{Weld stress} = \frac{Q}{t_w} = \frac{P}{l t_w}\sqrt{\left[\frac{\gamma y}{\beta l}\right]^2 + \left[\frac{1}{\alpha} + \frac{\gamma x}{\beta l}\right]^2} \; \check{S} F_{all} = 0.3F_u$$

$$\text{Allowable load, } P = \frac{F_{all}}{\sqrt{\left[\frac{\gamma y}{\beta l}\right]^2 + \left[\frac{1}{\alpha} + \frac{\gamma x}{\beta l}\right]^2}} l t_w = \frac{0.3\,(70) C_1 1}{\sqrt{\left[\frac{\gamma y}{\beta l}\right]^2 + \left[\frac{1}{\alpha} + \frac{\gamma x}{\beta l}\right]^2}} \frac{D}{16\sqrt{2}}$$

$$= \frac{0.928}{\sqrt{\left[\frac{\gamma y}{\beta l}\right]^2 + \left[\frac{1}{\alpha} + \frac{\gamma x}{\beta l}\right]^2}} C_1 l D = C C_1 l D$$

Ultimate Strength Method





Example

$P = 3\ 1.6$ k, $A = 10$ in, $l = 10$ in, $kl = 5$ in, $xl = 1\ .25$ in

$\alpha = 2$, $\beta = 0.\ 385$, $\gamma = 0.875$, $x = 1.25$ in, $y = 5$

for 3/8 fillet : $t_w = 0.26\ 5$ in $(D = 6)$

$$Q = \frac{P}{l}\sqrt{\left[\frac{\gamma y}{\beta l}\right]^2 + \left[\frac{1}{\alpha} + \frac{\gamma x}{\beta l}\right]^2} = 5\ 577 \text{ lb/in}$$

$$\text{Weld stress} = \frac{Q}{t_w} = 21\ 032 \text{ psi}$$

$$C = \frac{0.928}{\sqrt{\left[\frac{\gamma y}{\beta l}\right]^2 + \left[\frac{1}{\alpha} + \frac{\gamma x}{\beta l}\right]^2}} = 0.5258$$

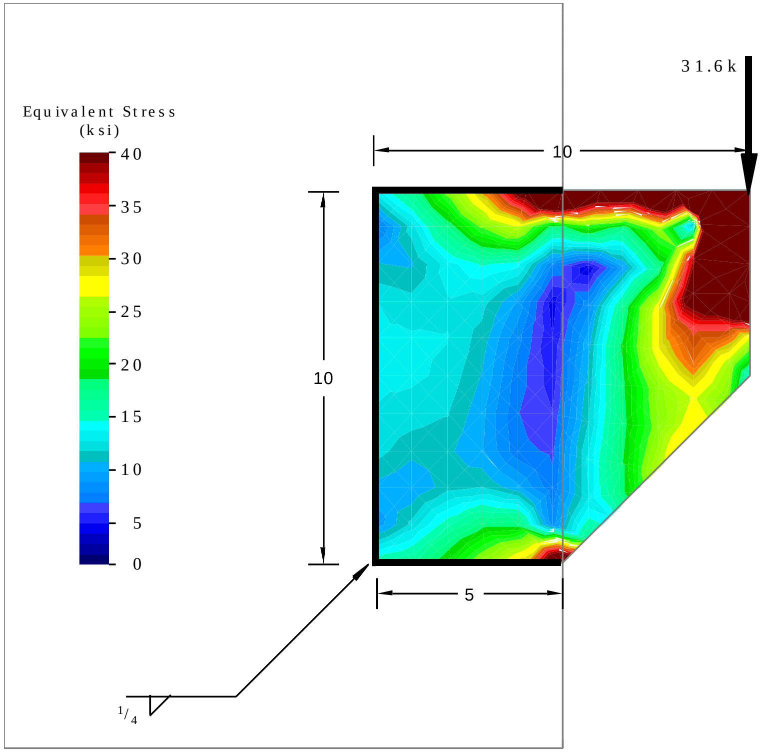
$= 0.\ 527$ (Table XVI AISC Manual 7th ed by interpolation)

Allowable weld load, $P = C C_1 l D = (0.\ 527)(1)(10)(6) = 3\ 1.6$ k

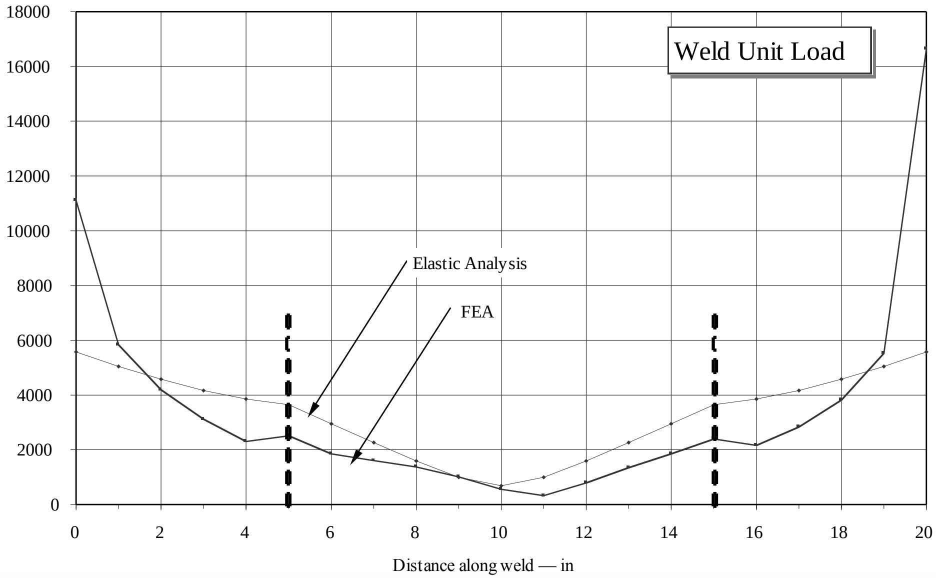
Using the ultimate strength method (Table XXIII AISC Manual 9th ed)

$C = 0.704$ $P = C C_1 l D = (0.7\ 04)(1)(10)(6) = 42\ .2$ k

Bracket Plate



- •3/8 Bracket plate fillet welded to rectangular base plate fixed at edges
- •Weld attachment simulated with rigid constraints
- •Weld force distribution compared to AISC Elastic method

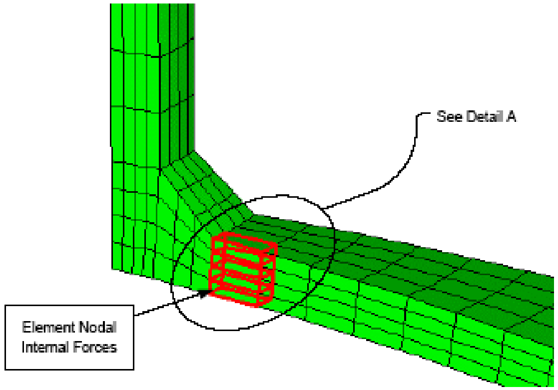


ASME Code Design

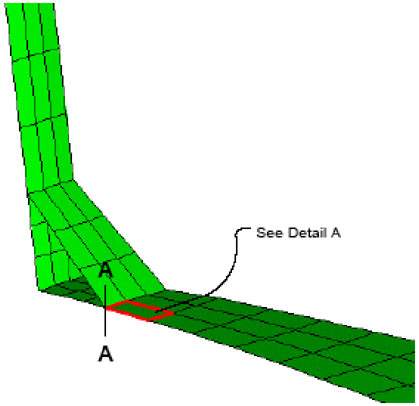
- Prescriptive provisions
  - Specific weld joint details
    - Flange attachment
    - Opening details
  - Weld details
    - Types
    - Sizes
  - Allowable stresses
    - Construction dependent
  - Quality assurance
    - Joint efficiencies

- Non Prescriptive Provisions
  - Attachments
    - Supports
    - Machinery
  - External loading
    - Piping loads
    - Impact
  - Unique construction
    - Non-circular openings
    - Proprietary items
  - Design by analysis (VIII-2)
    - Lower design margin
    - More restrictive quality assurance
    - Explicit weld analysis rules

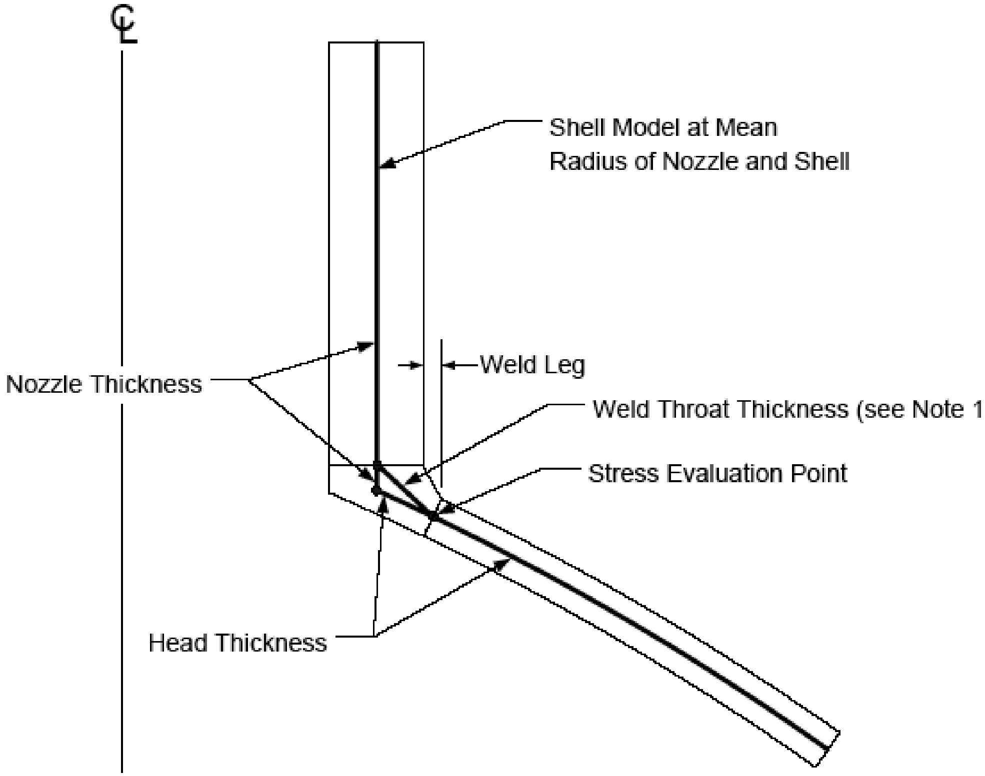
Explicit Modeling



Solid Model

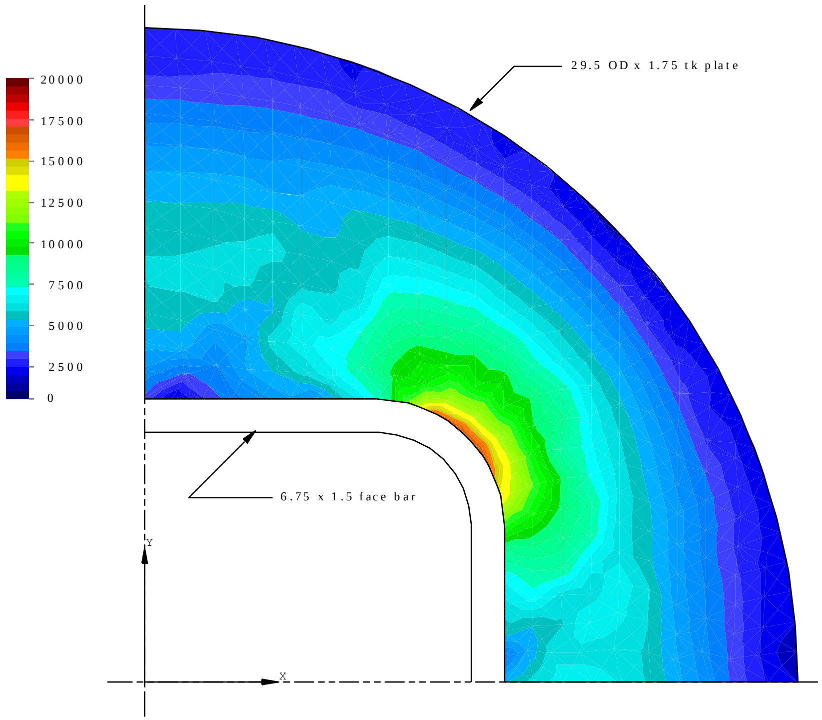


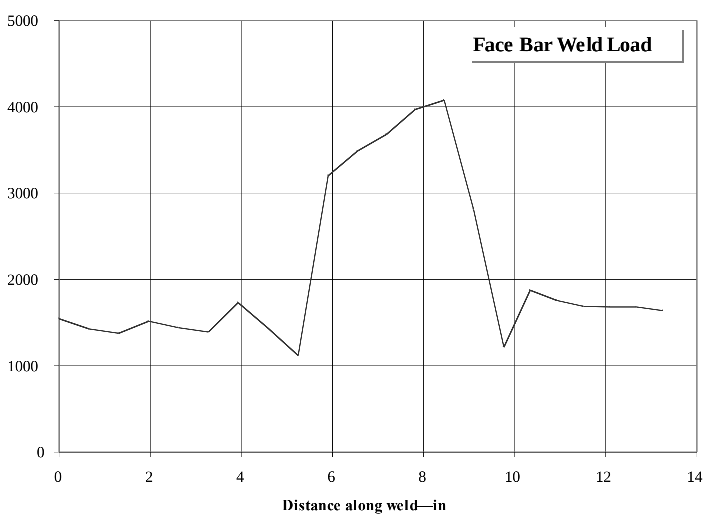
Shell Model



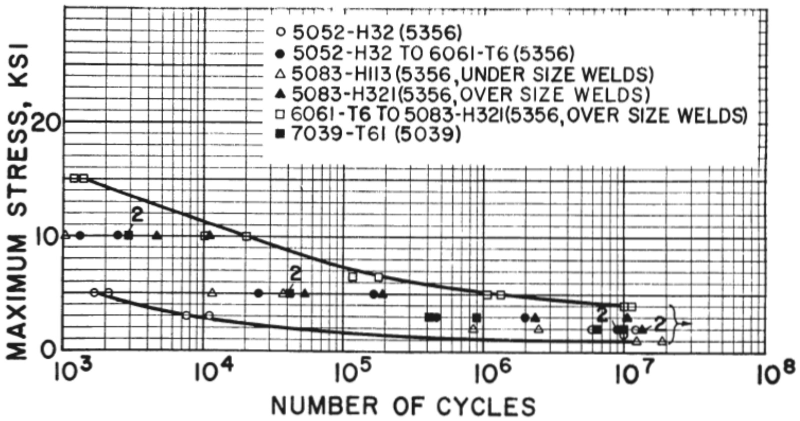
Non-Circular Opening

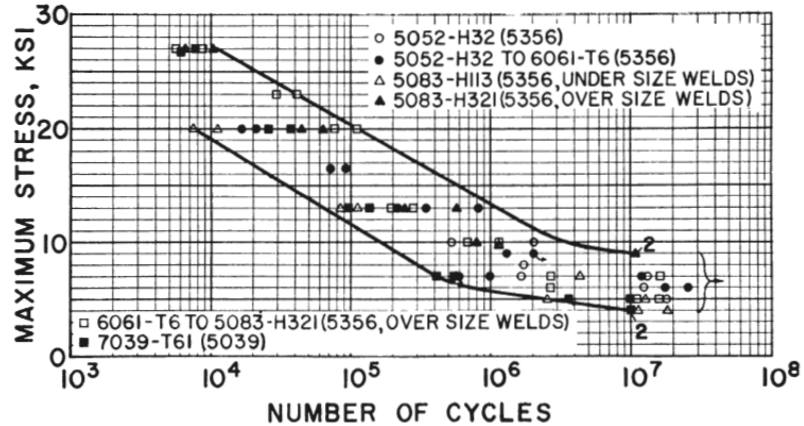
- Pressurized bulkhead 29.5 in OD x 1.75 in thick with reinforced 16.25 x 12.75 rectangular opening
- Face bar attachment simulated with rigid constraints
- Weld force distribution checked against ASME Code opening requirements

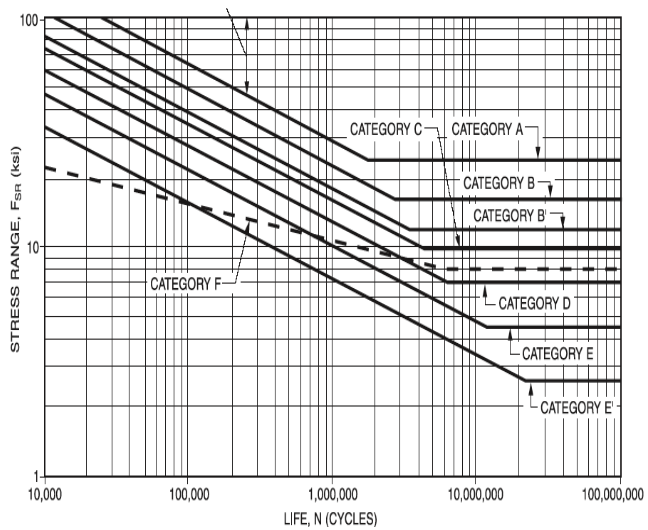


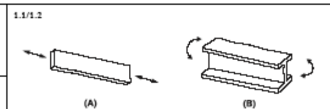
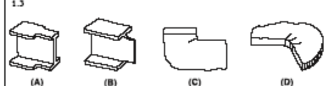


Fatigue AWS/AISC

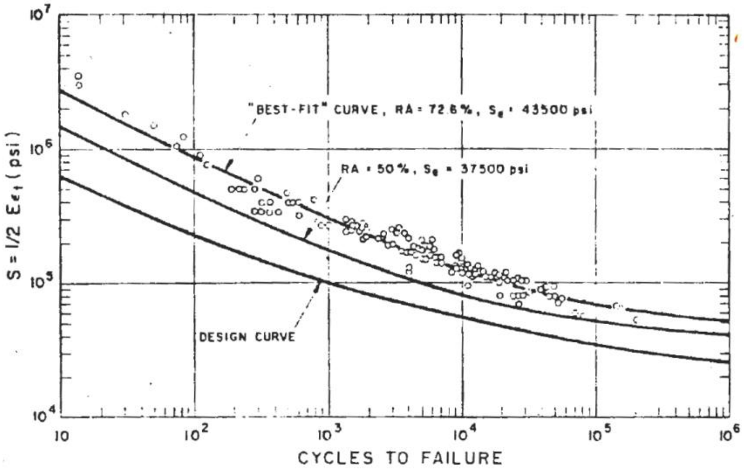






Description	Stress Category	Constant C_f	Threshold F_{TH} ksi [MPa]	Potential Crack Initiation Point	Illustrative Examples
Section 1—Plain Material Away from Any Welding					
1.1 Base metal, except non-coated weathering steel, with rolled or cleaned surface and rolled or flame-cut edges with ANSI smoothness of 1000 or less, but without re-entrant corners.	A	250×10^8	24 [166]	Away from all welds or structural connections	1.1/1.2  (A) (B)
1.2 Non-coated weathering steel base metal with rolled or cleaned surface and with rolled or flame-cut edges with ANSI smoothness of 1000 or less.	B	120×10^8	16 [110]	Away from all welds or structural connections	
1.3 Flame-cut re-entrant corners, except weld access holes, meeting the requirements of 2.16.5 with ANSI smoothness of 1000 or less.	B	120×10^8	16 [110]	From irregularities in surface of re-entrant corner	1.3  (A) (B) (C) (D)
1.4 Weld access holes made to the requirements of 2.16.5 and 5.17.1.	C	44×10^8	10 [69]	From irregularities in surface of re-entrant corner of weld access hole	1.4  (A) (B)

Fatigue ASME Code



ASME Code Fatigue rules originate from the Coffin-Manson rule: the product of the plastic strain amplitude (half the strain range under reversed loading) produced by a cyclic loading and the number of cycles to crack initiation equals half the fracture ductility:

$$\varepsilon_p\sqrt{N} = \frac{\varepsilon_f}{2} = \frac{1}{2}\ \mathrm{Ln}\left(\frac{100}{100 - RA}\right)$$

where:

- ε_p amplitude of plastic strain
- N number of cycles to crack initiation
- RA Reduction of area from tensile test
- ε_f fracture ductility

Taking the total strain amplitude as the sum of the plastic and elastic strain amplitudes and converting to stress by multiplying by the elastic modulus the cyclic stress amplitude to failure becomes

$$S = \frac{E}{4\sqrt{N}}\ \mathrm{Ln}\left(\frac{100}{100 - RA}\right) + \Delta s$$

For materials showing an endurance limit Δs is taken as the endurance limit

$$S = \frac{E}{4\sqrt{N}}\ \mathrm{Ln}\left(\frac{100}{100 - RA}\right) + S_e$$

B. F. Langer, 'Design of Pressure Vessels for Low Cycle Fatigue,' *J. of Basic Engineering*, ASME Transactions, September 1962.

Table 5.11 Ğ 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	1.5	NA	NA	NA	3.0	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	3.0	4.0

Table 5.12 Ğ 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
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 or ground weld 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 non-definable and/or receive no examination.

Notes:

1. Volumetric examination is RT or UT in accordance with Part 7.
2. MT/PT examination is magnetic particle or liquid penetrant examination in accordance with Part 7
3. VT examination is visual examination in accordance with Part 7.