Test Devices Inc.
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1.0 Purpose: The purpose of this engineering standard is to define the approved design analysis, manufacturing and inspection methods for safety critical weld joints in TDI products.

2.0 Scope: This engineering standard outlines all approved methods for analyzing, manufacturing and inspecting the safety critical weld joints. Test Devices documentation, including drawings, will reference this specification and specify the class to be used.

Safety critical Weld Joints refers to any welded joints or parts that construct load bearing structures or safety critical structures, which includes, but not limited to the following:

- Spin pit lid lifter parts
- Spin pit vacuum chamber
- Spin pit containment liner

3.0 Definitions:

- AWS: American Welding Society
- IIW: International Institute of Welding
- NDI: None-Destructive Inspection
- UT: Ultrasonic Test (or Inspection)
- FPI: Florescent-die Penetrant Inspection
- MPI: Magnetic Particle Inspection

4.0 Responsibility:

It is the responsibility of Test Devices' engineering manager to ensure this standard is maintained and updated continuously. As this work involves safety critical features, the

APPROVALS			
Engineering	Hiro Endo, CTO	HE 3/1/2018	Date
Quality	Enzo Alami, Quality Manager	Enzo Alami Digitally signed by Enzo Alami Date: 2018.03.01 10:11:20 -05'00'	Date

Revision Log				
Revision	Summary of Changes	Approved By Process Owner (s)	Approved By VP Quality / Mgt Rep	Rev. Release Date
Initial Issue		HE	Enzo Alami Digitally signed by Enzo Alami Date: 2018.03.01 10:11:41 -05'00'	3/01/18

reviewing and approving of the analysis and/or manufacturing and inspection instructions must be done by a senior level engineer (or higher ranked engineer) with a directly relevant experience and knowledge.

5.0 Engineering Standard: The list below defines the acceptable design analysis, welding and weld inspection methods approved by Test Devices' engineering department. Any alternate methods must be requested and approved by Test Devices' engineering department before the alternate methods are applied.

5.1 Approved Weld Analysis Method

- All safety critical welded structure shall be analyzed by using the FEA with effective notch stress method prescribed by the IIW [1].
- Model both weld root and toe and compute fully converged stresses at the features.
- Use keyhole design to model the welds using the method specified in the IIW [1], Chapter 3.4. See Figure-1 for an example of the welded joints models.
- Consider all relevant loading scenario. At minimum evaluate and assess the structure against both static/quasi-static overload and fatigue conditions.
- For the fatigue analysis use appropriate weld fatigue strength curves for the material defined in the IIW, see Table-1 (ref [1], Table 3.1). NOTE: For steel, use FAT 225 (Figure-2).
- An example of weld analysis work for a lid lifter arm (steel structure) is attached in Appendix-A.

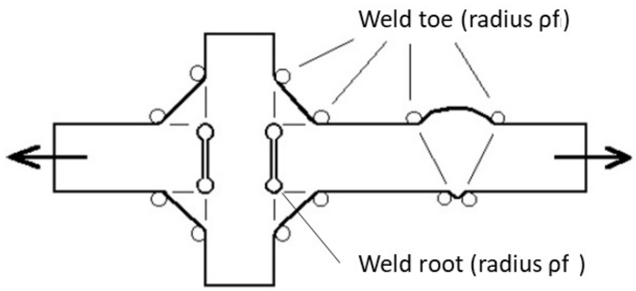

Figure-1: An example of effective notch model.

$\rho f = \rho + s\,\rho^*$

ρf: Representative notch radius (mm)
ρ: Actual notch radius (assume 0mm)
P*: Reference radius (0.4mm)
s: Stress multiaxiality & strength factor (assume 2.5 for Steel)

Therefore, the representative radius of the welds is: ρf = 0 + 2.5*0.4 = 1.0mm

Characteristic fatigue strength (P_s = 97.7%, $N = 2{\cdot}10^6$) for welds of different materials based on maximum principal stress

Material	Characteristic fatigue strength for r_{ref} = 1 mm	Characteristic fatigue strength for r_{ref} = 0.05 mm
Steel	FAT 225	FAT 630
Aluminium alloys	FAT 71	FAT 180
Magnesium	FAT 28	FAT 71

Table-1: Characteristic fatigue strength (Ps = 97.7%, N = 2·106) for welds of different materials based on maximum principal stress.

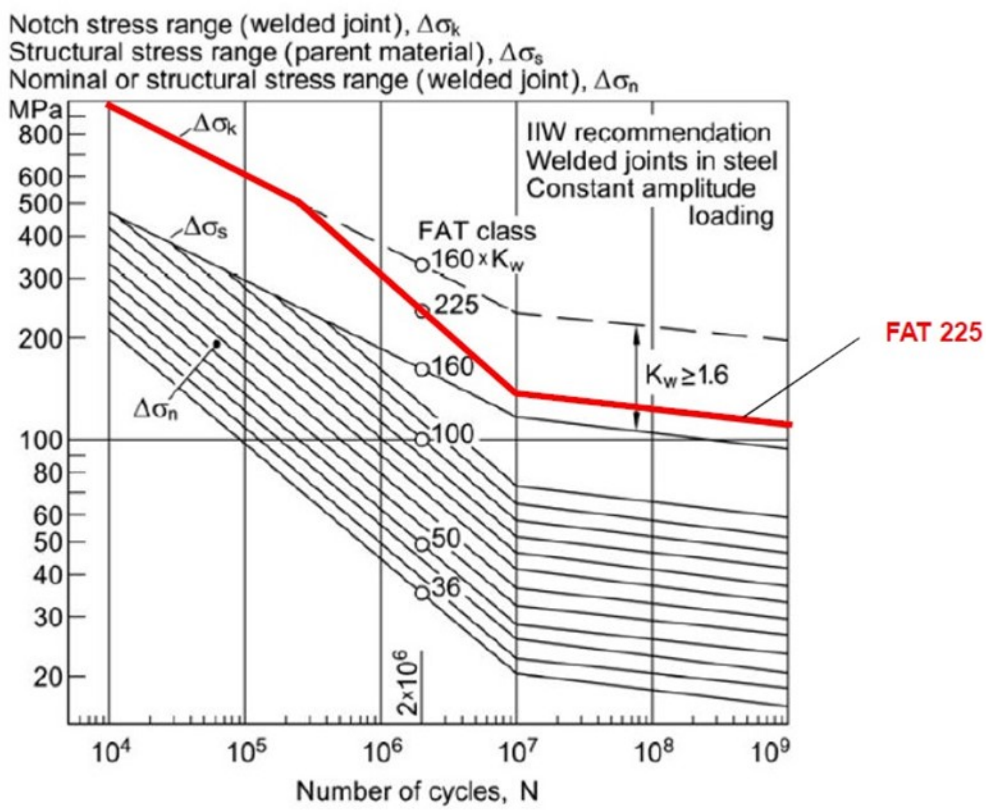

Figure-2: FAT225 Fatigue Curve (Steel) [3].

5.2 Applicable Welding Standard

- Test Devices require all safety critical welded joint to be manufactured in conformance with the AWS standard [2].

- For the manufacturing of welded steel structures, use ASW D1.1. NOTE: The code is not intended to be used for the following:
  - Steels with a minimum yield strength greater than 100 ksi (690 MPa).
  - Steels less than 1/8 in. (3 mm) thick – refer to AWS D1.3.
  - Pressure vessels or pressure piping.

- For the welding of metals other than carbon or low-alloy steels refer to appropriate standard.

5.3 Applicable Weld Inspection Standard

- Test Devices require all safety critical welded joint to be inspected in conformance with the AWS standard, chapter 6 [2].

- Prior to commencing the welding work, Test Devices require welders to submit the following records:
  - Copies of WPS (Welding Procedure Specifications) of the relevant welds
  - Copies of Procedure Qualification Record (PQR) and relevant test (no older than 2 years)

- Unless otherwise specified, all welding inspections shall be performed by assuming cyclically loaded condition.

- Unless otherwise specified, perform MPI (for steel) and FPI (for none ferrous materials) on the root welds prior to adding the layers and the final surface after the welding is fully completed.

- Unless otherwise specified, perform NDIs (UT and/or radiography) on the welded joints of safety critical parts.

6.0 Referenced Documents:

1. "IIW Guideline for the assessment of weld root fatigue", W. Fricke, Welding in the World, Le Soudage Dans Le Monde · November 2013, DOI: 10.1007/s40194-013-0066-y

1. "Structural Welding Code Steel", AWS D1.1/D1.1M:2015, An American National Standard, second printing, March 2016

2. "Fatigue failure analysis of fillet welded joints used in offshore structures" E. Djavit & E. Strande, Master's thesis, CHALMERS UNIVERSITY OF TECHNOLOGY Göteborg, Sweden 2013, Master's Thesis X-13/294

3. "Fatigue of Weldments", G. Glinka, June 2nd – 6th, 2014, Lecture Notes, University of Waterloo, Canada

4. "Fatigue Analysis of a Welded Structure in a Random Vibration Environment", Michael Bak, ANSYS Users Conference Framingham, MA June 13, 2013

5. "AWS D.1 Str Welding Code - Do you know what it really says", W. J. Oliphant, PE, AWS-CWI, F.SEI, F.ASCE ReliaPOLE Inspection Services Company, LLC

7.0 Appendix-A: An example of welded joint analysis

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Weld Integrity Analysis of 60in Spin Pit Lid Lifter Arm
2000-12-2066

2/23/2018

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Equipment Info

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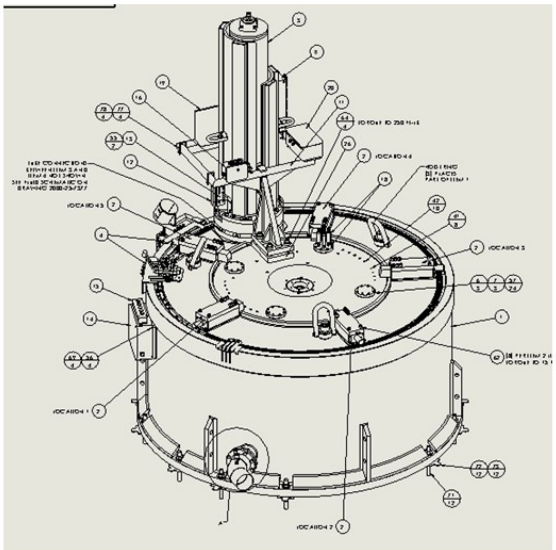
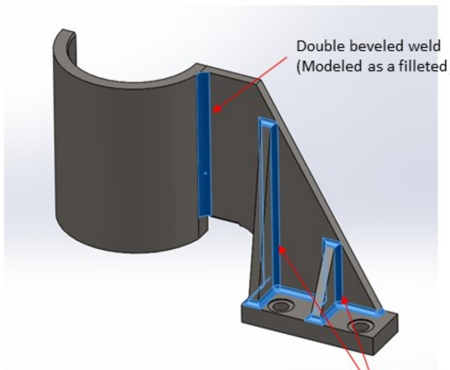


Part: TDI 60in Spin pit, Lid Lifter Arm

Material: ASTM A36 steel / Weldment
- Modulus: 29,000ksi
- Yield Limit: 36~50ksi
- UTS: 58~80ksi



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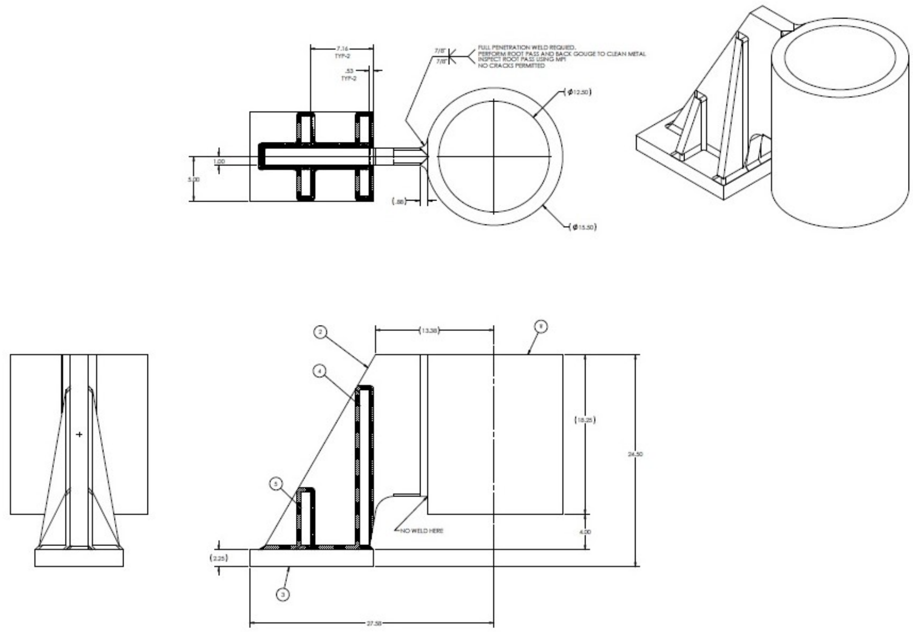
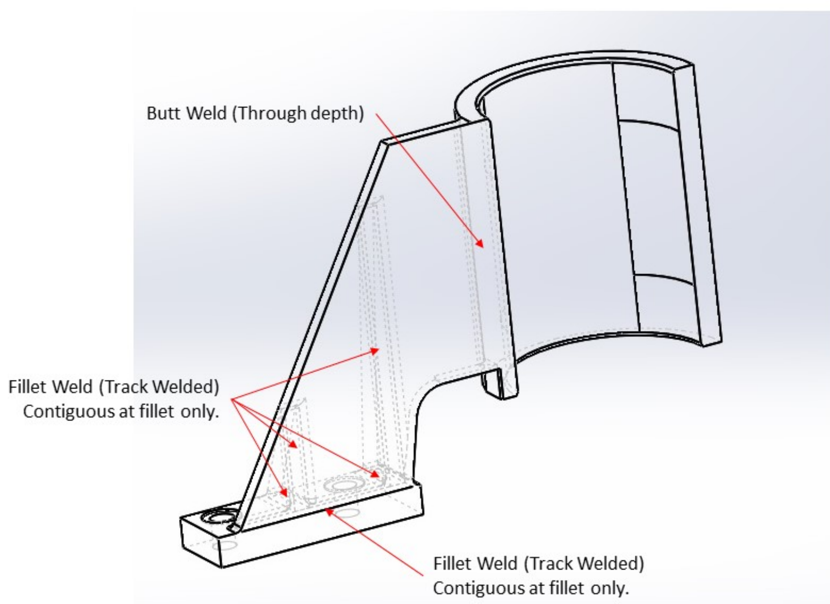
Design Details



Boundary & Loading Conditions



Equipment Info

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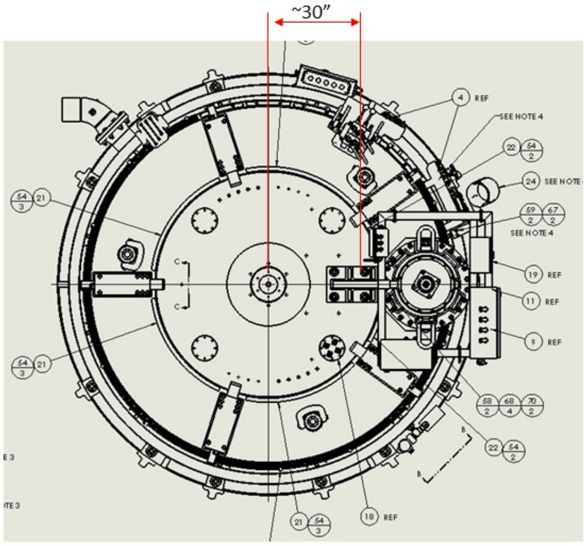
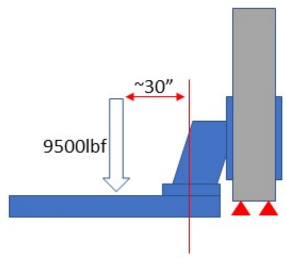


Max mass on the lid lifter arm: 9500lb
Cantilever arm distance: ~30"

Load calculations:

- Vertical Load: 9500lbf downward
- Moment: 9500lbf x 30"/12 = 23,750lbf-ft



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Boundary & Loading Conditions

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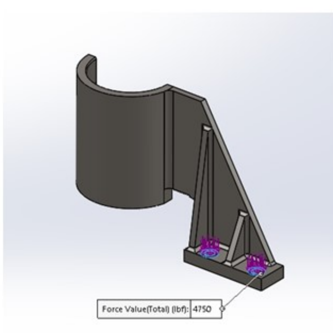
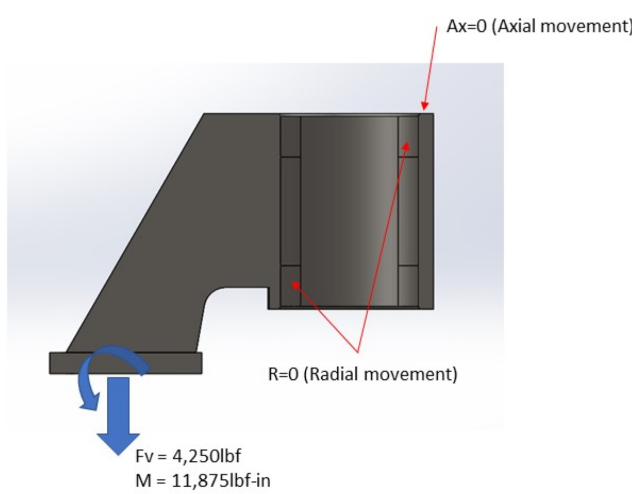


NOTE:

- The vertical load applied at bolt holes.
- Moments are applied about the mid-distance of the bolt holes on the lower face of the arm



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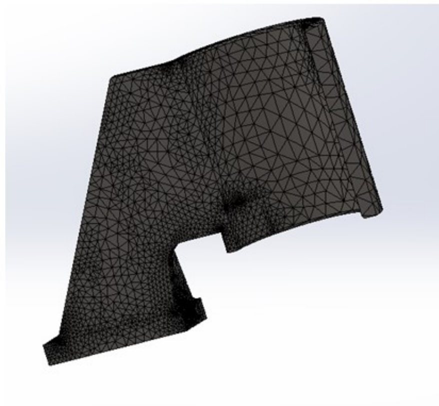
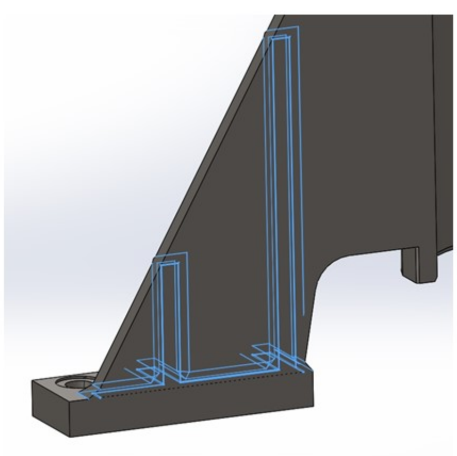
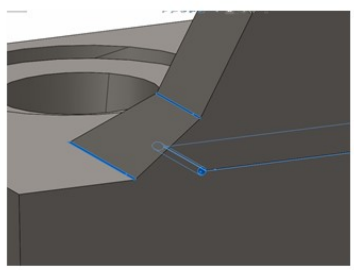
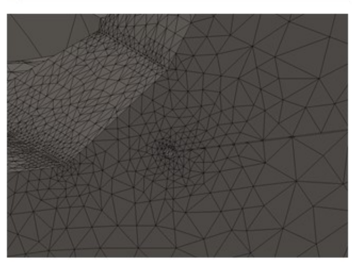
FEA Mesh

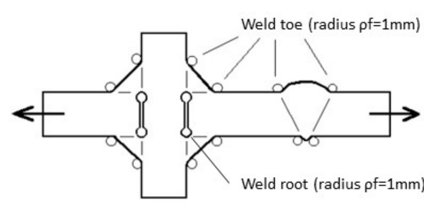


FE Model of Welds









ρf = ρ + s ρ*

ρf: Representative notch radius (mm)
ρ: Actual notch radius (assume 0mm)
P*: Reference radius (0.4mm)
s: Stress multiaxiality & strength factor (assume 2.5 for Steel)

Therefore, the representative radius of the welds is:
ρf = 0 + 2.5*0.4 = 1.0mm

Ref: [1, 2, 3, 4, 5]

Deflection Shape (x50)

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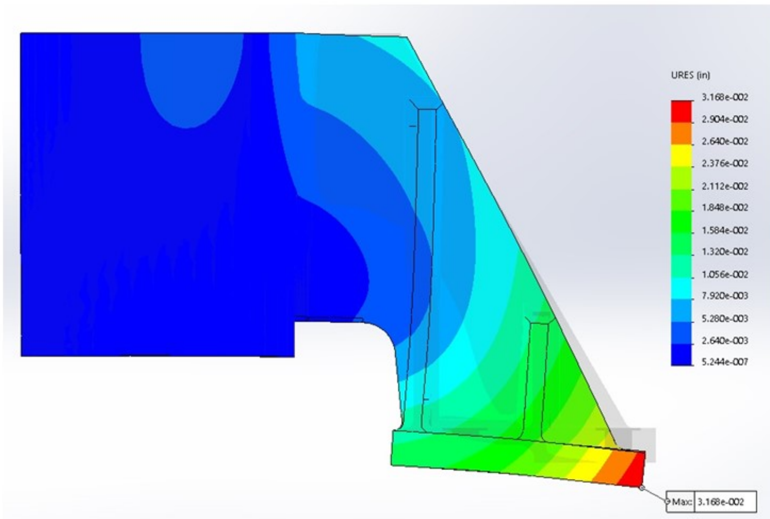

Observation

- Deformation shape in line with expected behavior…

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FEA (SVM vs. Yield Limit)

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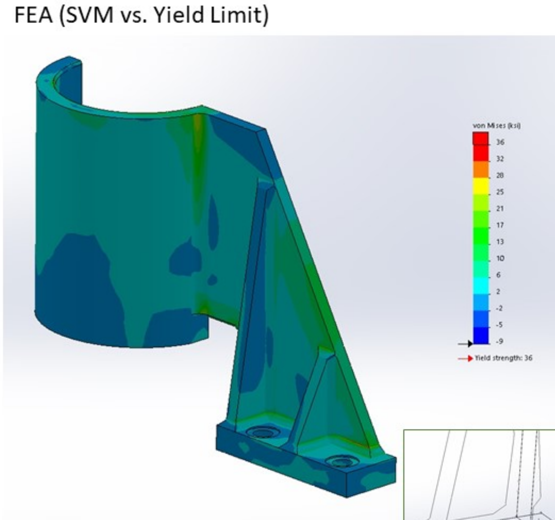

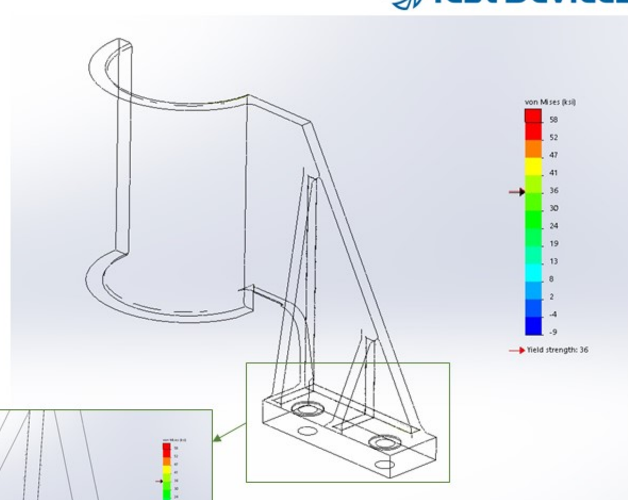

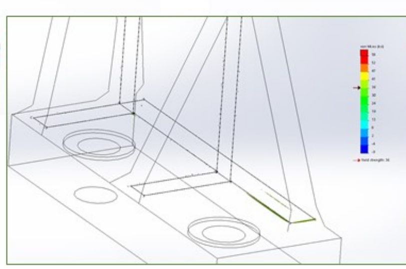

- Some localized yielding at weld roots and toes.
- Unlikely to collapse from overload, but need to assess for fatigue life.

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FEA (P1 vs. UTS)

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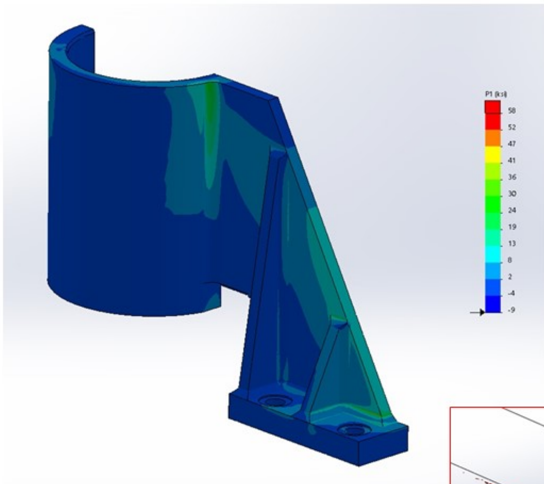

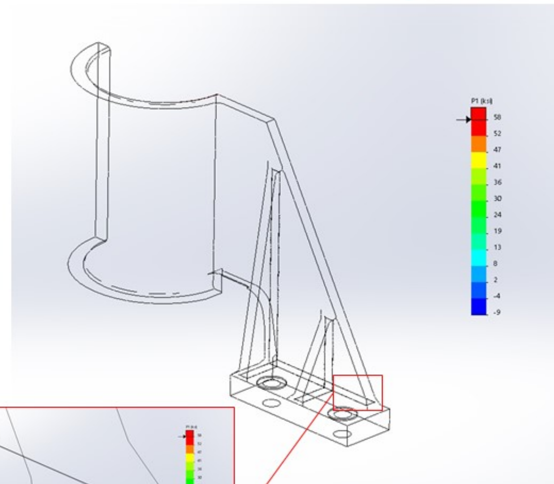

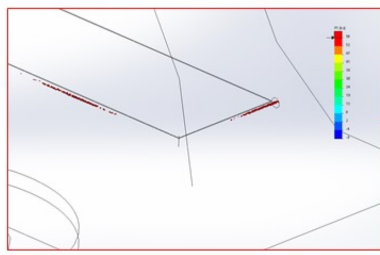

- Stress exceedance (UTS) in concentrated areas.
- Unlikely to collapse from overload, but need to assess for fatigue life.

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Fatigue Assessment of Welded Joints:

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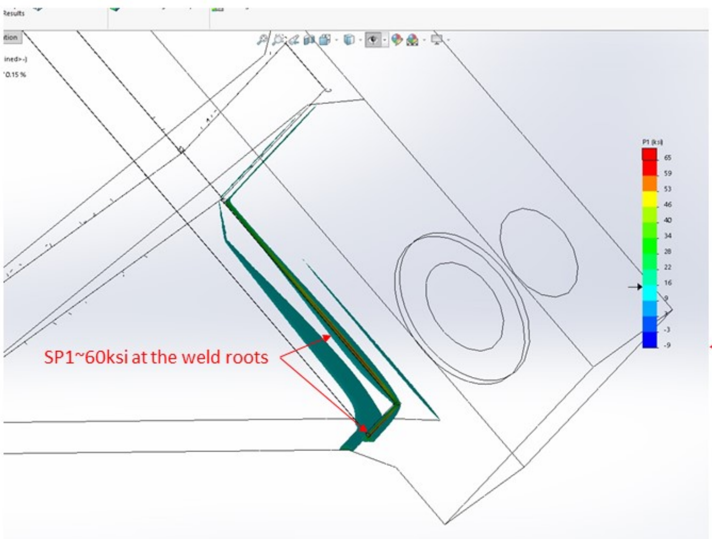
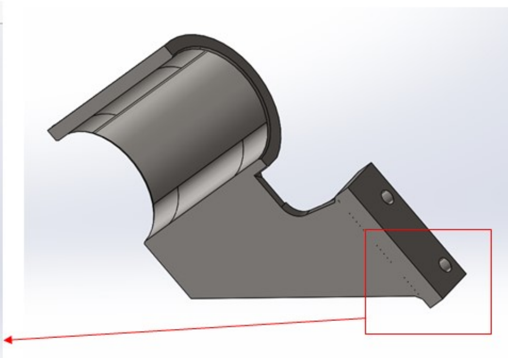
FEA (Stress Concentrations, P1)





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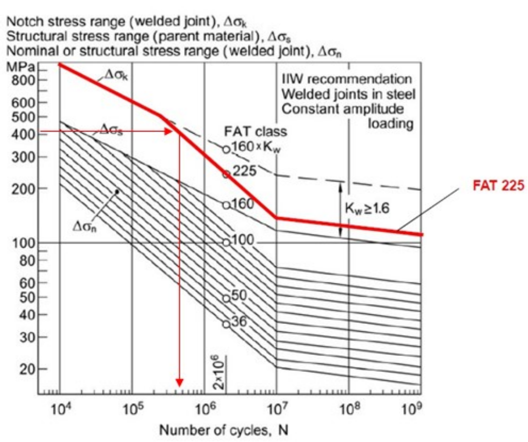
FEA (P1 vs. UTS)

Table 3.1: Characteristic fatigue strength (P_s = 97.7%, $N = 2 \cdot 10^6$) for welds of different materials based on maximum principal stress

Material	Characteristic fatigue strength for r_{ref} = 1 mm	Characteristic fatigue strength for r_{ref} = 0.05 mm
Steel	FAT 225	FAT 630
Aluminium alloys	FAT 71	FAT 180
Magnesium	FAT 28	FAT 71



- FAT 225 is the recommended S-N curve if using the effect notch stress approach with welds in steel.
- The curve represents a survival probability of 97.7% and a standard deviation of log N = 0.206.

- Results:
  - Lid Lift Arm Stress: 60ksi (414MPa)
  - Estimated weld root life (crack initiation) 40,000~50,000 loading cycles.

  - Assuming 10 cycles per day, the nominal average annual usage of the spin rig would be 10x5x52 = 2600/year.
  - Estimated life to crack initiation = 15~20 years.

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Conclusions & Recommendations

- The result of this study showed that the lid lift arm has adequate strength and life to warrant a safe lifting of the designed weight for 60in spin pit.
- The Following conclusions were drawn:
  - The lid lift arm can withstand the designed max weight.
  - 15~20 years of equipment life (crack initiation) was calculated with conservatism.
- The above assessment assumes good quality welding work. To ensure this, the following recommendations should be followed:
  - Inquire update WPS & weld test results (directly relevant to the type and the size of the weld work).
  - Perform weld inspection following the AWS D1.1 (for steel).
  - Recommend NDT in addition to the visual inspection.
    - For the lid lifter arm, the following NDT are recommended:
      - Buttweld – Visual, Mag Particle & UT (from the ID of the cylinder).
      - Fillet weld – Visual & Mag particle – (No UT as access is limited due to the geometry of the part)

Ref: [6, 7]

Weld Inspection Methods:

Table 1 - Reference Guide to Major Methods for the Nondestructive Examination of Welds

Inspection Method	Equipment Required	Enables Detectiort of	Advantages	Limitations	Remarks
Visual	Magnifying glass Weld sizing gauge Pocket rule Straight edge Workmanship standards	Surface flaws - cracks, porosity, unfilled craters, slag inclusions Warpage, underwelding, overwelding, poorly formed beads, misalignments, improper fitup	Low cost. Can be applied while work is in process, permitting correction of faults. Gives indication of incorrect procedures.	Applicable to surface defects only. Provides no permanent record.	Should always be the primary method of inspection, no matter what other techniques are required. Is the only "productive" type of inspection. Is the necessary function of everyone who in any way contributes to the making of the weld.
Radiographic	Commercial X-ray or gamma units made especially for inspecting welds, castings and forgings. Film and processing facilities. Fluoroscopic viewing equipment.	Interior macroscopic flaws - cracks, porosity, blow holes, nonmetallic inclusions, incomplete root penetration, undercutting, icicles, and burnthrough.	When the indications are recorded on film, gives a permanent record. When viewed on a fluoroscopic screen, a low-cost method of internal inspection	Requires skill in choosing angles of exposure, operating equipment, and interpreting indications. Requires safety precautions. Not generally suitable for fillet weld inspection.	X-ray inspection is required by many codes and specifications. Useful in qualification of welders and welding processes. Because of cost, its use should be limited to those areas where other methods will not provide the assurance required.
Magnetic Particle	Special commercial equipment. Magnetic powders - dry or wet form; may be fluorescent for viewing under ultraviolet light.	Excellent for detecting surface discontinuities - especially surface cracks.	Simpler to use than radiographic inspection. Permits controlled sensitivity. Relatively low-cost method.	Applicable to ferromagnetic materials only. Requires skill in interpretation of indications and recognition of irrelevant patterns. Difficult to use on rough surfaces.	Elongated defects parallel to the magnetic field may not give pattern; for this reason the field should be applied from two directions at or near right angles to each other.
Liquid Penetrant	Commercial kits containing fluorescent or dye penetrants and developers. Application equipment for the developer. A source of ultraviolet light - if fluorescent method is used.	Surface cracks not readily visible to the unaided eye. Excellent for locating leaks in weldments.	Applicable to magnetic and nonmagnetic materials. Easy to use. Low cost.	Only surface defects are detectable. Cannot be used effectively on hot assemblies.	In thin-walled vessels will reveal leaks not ordinarily located by usual air tests. irrelevant surface conditions (smoke, slag) may give misleading indications.
Ultrasonic	Special commercial equipment, either of the pulse-echo or transmission type. Standard reference patterns for interpretation of RF or video patterns.	Surface and subsurface flaws including those too small to be detected by other methods. Especially for detecting subsurface lamination-like defects.	Very sensitive. Permits probing of joints inaccessible to radiography.	Requires high degree of skill in interpreting pulse-echo patterns. Permanent record is not readily obtained.	Pulse-echo equipment is highly developed for weld inspection purposes. The transmission-type equipment simplifies pattern interpretation where it is applicable.

References:

1. "RECOMMENDATIONS FOR FATIGUE DESIGN OF WELDED JOINTS AND COMPONENTS", A. Hobbacher, International Institute of Welding (IIW), Dec 2008, IIW document IIW-1823-07, ex XIII-2151r4-07/XV-1254r4-07
2. "IIW Guideline for the assessment of weld root fatigue", W. Fricke, Welding in the World, Le Soudage Dans Le Monde · November 2013, DOI: 10.1007/s40194-013-0066-y
3. "Fatigue failure analysis of fillet welded joints used in offshore structures" E. Djavit & E. Strande, Master's thesis, CHALMERS UNIVERSITY OF TECHNOLOGY Göteborg, Sweden 2013, Master's Thesis X-13/294
4. "Fatigue of Weldments", G. Glinka, June 2nd – 6th, 2014, Lecture Notes, University of Waterloo, Canada
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7. "Structural Welding Code Steel", AWS D1.1/D1.1M:2015, An American National Standard, second printing, March 2016