JTC Engineering Investigation

Water Transfer Tubes Crack along Welded Joints, Causing a Leak

Investigation #: ____

Investigation Leader: Jessica Nicholson

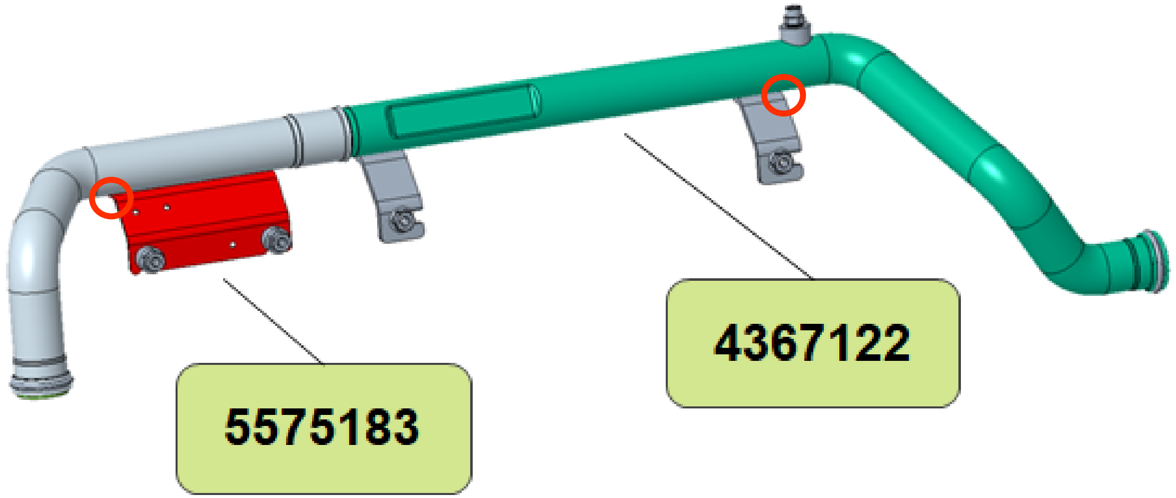
Date Opened: 6/21/2021

Date Closed: ____

Background Information

■ = Censored for confidentiality

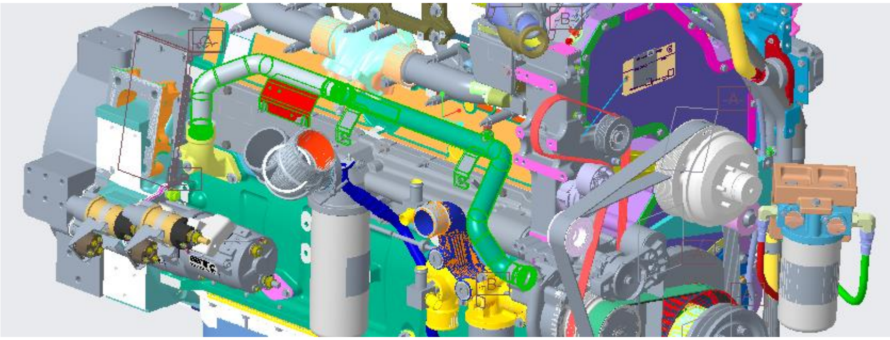
Failed Components



- Two water transfer tubes
  - Fails along circled weld joints
- Configurations:
  - 11BX03 – Rottweiler e5
  - 18BX03 – Pit Bull e6
  - 17MX03 – X15 Marine
  - 20CX03 – Tier 2 Industrial
  - 21GX03 – Genset

ID Type	Part Number	Quantity	Noun Name	Effect Code
21-1	5575183	1	Water Transfer Tube	10
15-1	3683814	1	O-ring seal	10
13	5575184	1	Water Transfer Tube	30
10	5575331	1	Piece (Bracket)	30
10	5575332	1	Piece (Tube end)	30
10	5575333	1	Piece (Tube)	30

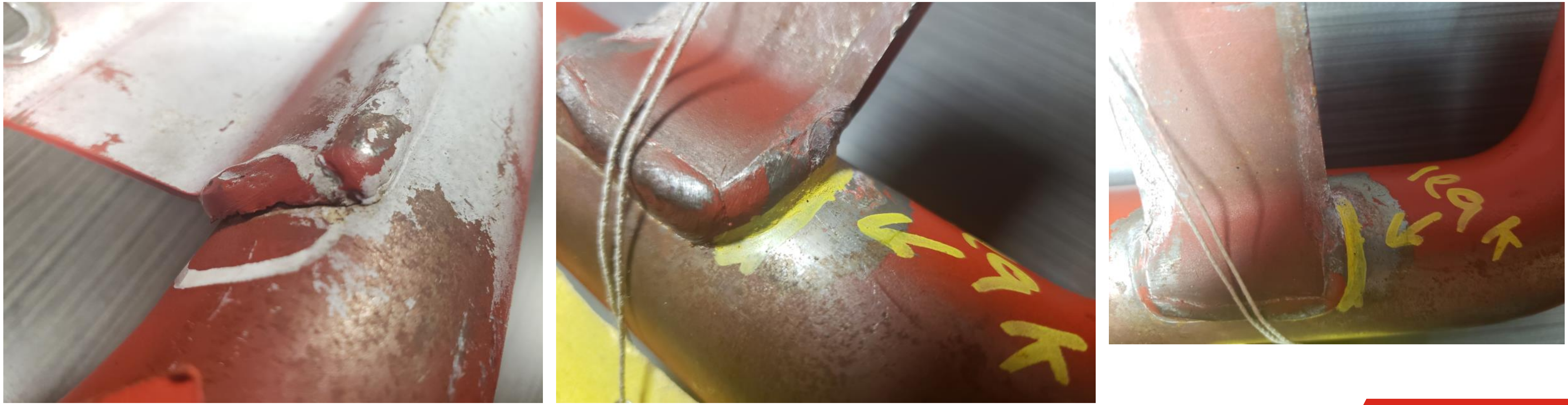
ID Type	Part Number	Quantity	Noun Name	Effect Code
21-1	4367122	1	Water Transfer Tube	10
15-1	3683814	1	O-ring seal	10
15-1	5647446	1	O-ring seal	10
13	4367123	1	Water Transfer Tube	10
10	4367124	1	Piece (Tube)	30
10	4367139	2	Piece (Bracket)	30
10	4367140	1	Piece (Boss)	30



Water transfer tube in the Rottweiler, obstructive parts hidden

Failure Description

- Fail Code: KCTA
- Both parts crack along weld joint connecting bracket to tube
- Crack can get worse and lead to failure if not identified and fixed
- Leaks are commonly reported along this crack



Claims Research

Search Criteria and Results

- Claims data search to identify leak along weld failures
  - Heavy duty engine group, 15 Liter, Plant: JEP
  - Build month range: 01/2015 to 07/2021
  - Failure code: KCTA
- All regions / worldwide
  - Build volume: 552,078, Claims: [redacted]
  - Average RPH = [redacted]
  - Average cost per claim = $475.43, Average CPE = $0.42
- Australia only
  - Build volume: 17,934, Claims: [redacted]
  - Average RPH = [redacted]
  - Average cost per claim = $477.65, Average CPE = $12.28

Worldwide vs Australia RPH Plots

[redacted]

- Build volume: 552,078
- Claims: [redacted]
- Minimal failure rate

- Build volume: 17,934
- Claims: [redacted]
- Significant failure rate

Worldwide vs Australia CPE Plots

[redacted]

- Build volume: 552,078
- Claims: [redacted]
- Minimal warranty cost

- Build volume: 17,934
- Claims: [redacted]
- Significant warranty cost

Results

- Significantly higher failure rate and CPE in Australia
- Majority of KCTA claims have failure mode of leak along welds
- Engine configurations experiencing failure
    - Rottweiler (D103011BX03), [redacted] out of [redacted] total claims
- Number of Rottweiler configurations bought by location
    - Of build volume in all regions, 42,021 out of 552,078 (7.6%)
    - Of build volume in Australia, 15,788 out of 18,153 (87%)

- Rottweiler engines experience significantly more failure than all other configurations
- Most likely cause of the higher failure rate in Australia

Worldwide vs Australia RPH Plots, Rottweiler Only

[redacted]

- Build volume: 42,021
- Claims: [redacted]
- Significant failure rate

- Build volume: 15,788
- Claims: [redacted]
- Significant failure rate

Worldwide vs Australia CPE Plots, Rottweiler Only

[redacted]

- Build volume: 42,021
- Claims: [redacted]
- Significant warranty cost

- Build volume: 15,788
- Claims: [redacted]
- Significant warranty cost

RPH Plot Excluding Australia, Rottweiler Only

[redacted]

- RPH in all regions besides Australia for Rottweiler engines
- Less significant failure rate

Conclusions

- Rottweiler engines experience
  - A slightly higher failure rate in Australia than worldwide
  - A significantly higher failure rate in Australia than all other regions
- Australia experiences a higher failure rate among
  - All engine configurations, primarily due to a greater proportion of Rottweiler purchases
  - Rottweiler engines, indicating a location-related cause of failure
- Failure modes are both:
  1. A fault of the water transfer tubes in the Rottweiler engine
  2. A location-related cause of failure in Australia

Component Change History vs Claims Research

- PPS Changes below
- No VPCR history based on part numbers and name
- No upward trends in claims research that correlate to these changes

Table 1: Part Change History

Part Number	P-Phase	O-Phase	ESN 1st Date	Primary Change
5575183	Jun-19	NA	-	Added holes in bracket for fur tree
4393526	Jul-16	Oct-19	1/5/2017	Bracket hole change shamrock to Slot
4386561	Aug-15	Jul-16	-	Thinner Bracket (Cass)
3688227	Mar-12	Aug-15	-	
Part Number	P-Phase	O-Phase	ESN 1st Date	Primary Change
4367122	Jun-14	NA	3/3/2015	O-ring grove optimization
3688228	Mar-12	14-Jun	-	

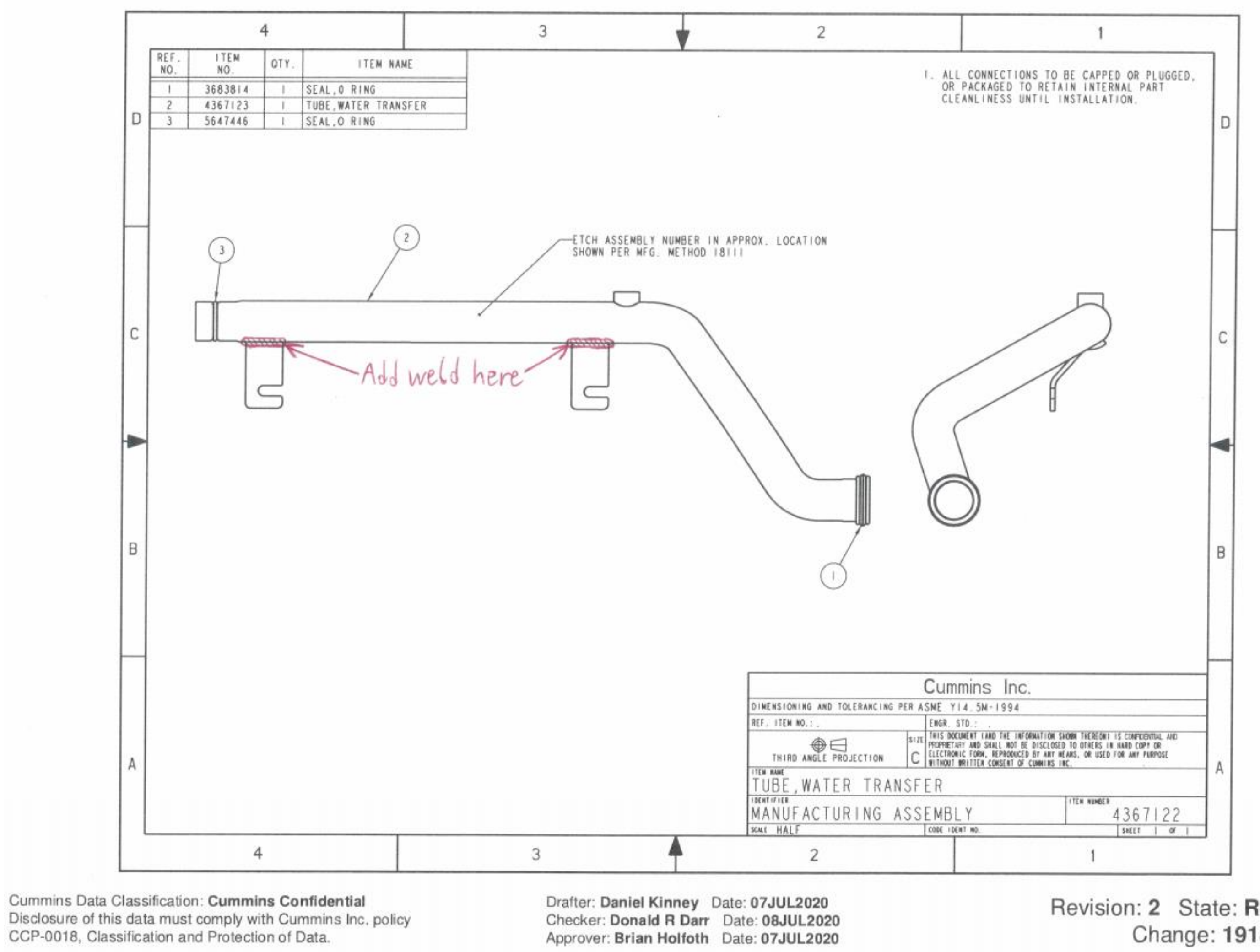
Step 3 (Short-Term) Solution

Step 3 Solution

- Failure mode is most likely a form of excessive stress or low material strength due to quality issues
- Create additional welds behind each bracket to secure to the pipe
- This temporary solution will create a stronger joint to resist failure due to stress or low strength while I investigate the cause of the weld cracking

- Suppliers: [redacted]
  - 5575183:
  - 4367122:

Step 3 Solution – Long Tube



REF. NO.	ITEM NO.	QTY.	ITEM NAME
1	3683814	1	SEAL,O RING
2	4367123	1	TUBE,WATER TRANSFER
3	5647446	1	SEAL,O RING

1. ALL CONNECTIONS TO BE CAPPED OR PLUGGED, OR PACKAGED TO RETAIN INTERNAL PART CLEANLINESS UNTIL INSTALLATION.

ETCH ASSEMBLY NUMBER IN APPROX. LOCATION SHOWN PER MFG. METHOD 18111

Cummins Inc.

DIMENSIONING AND TOLERANCING PER ASME Y14.5M-1994

REF. ITEM NO.: .

ENGR. STD.: .

THIRD ANGLE PROJECTION

SIZE C

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ITEM NAME: TUBE,WATER TRANSFER

IDENTIFIER: MANUFACTURING ASSEMBLY

ITEM NUMBER: 4367122

SCALE: HALF

CODE IDENT NO.

SHEET 1 OF 1

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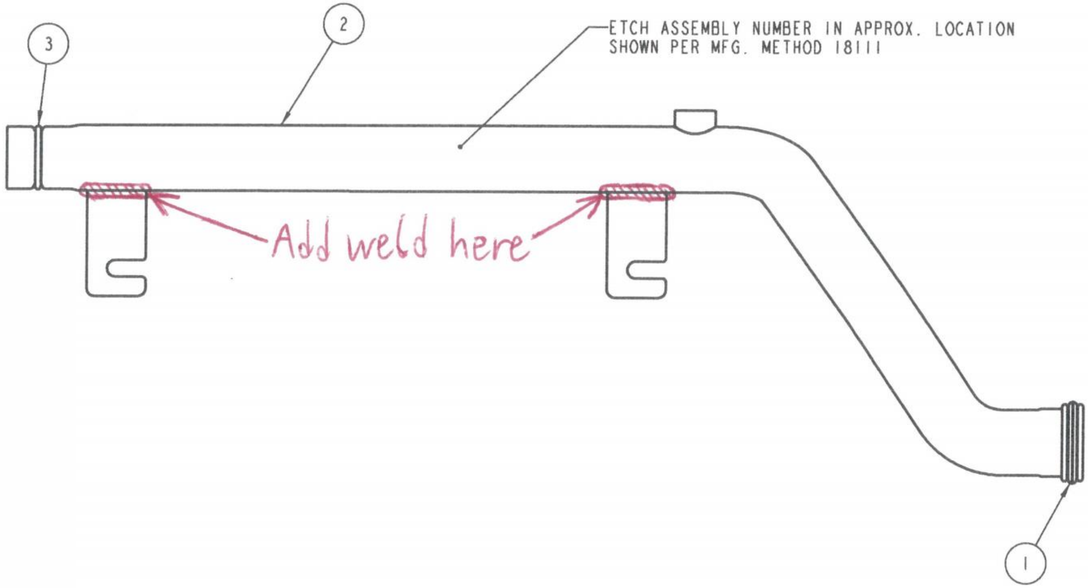
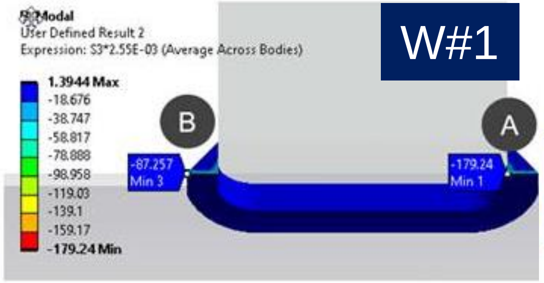
Drafter: **Daniel Kinney** Date: **07JUL2020**
Checker: **Donald R Darr** Date: **08JUL2020**
Approver: **Brian Holfoth** Date: **07JUL2020**

Revision: **2** State: **Released**
Change: **191850-340**



Step 3 Validation – Long Tube



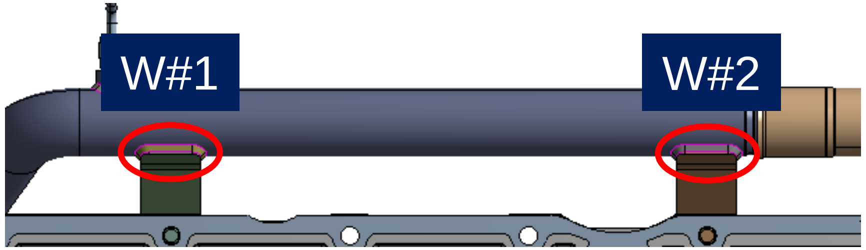
Max stress observed on Root (A) & toe location(B)

Max stress observed on Root (A) & toe location(B)

- Supplier conducted a comparative ANSYS analysis on current welded joint vs joint with additional weld
  - Evaluates the impact of the additional weld on stress within the system
- Found average stress acting upon weld toe and throat of each welded joint
  - Given same applied force of 10G on each system for alternating stress
  - Hot spot method used to find mean stress
- Generated Goodman diagrams with mean and alternating stress limits
  - Compares level of stress acting upon joints of current design vs additional weld
  - Determines how likely each design is to experience fatigue stress at given force

- Joints with the additional weld experience **significantly less stress** and are less likely to fail due to fatigue stress

Step 3 Validation – Long Tube

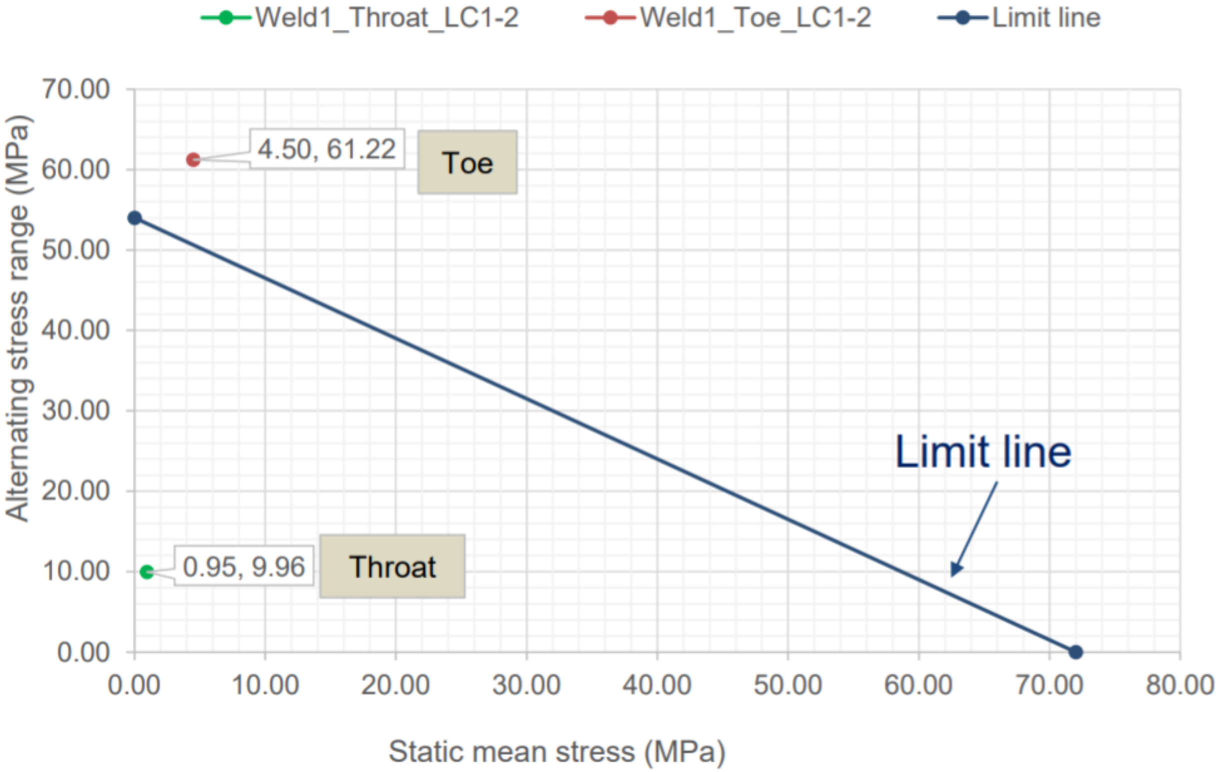


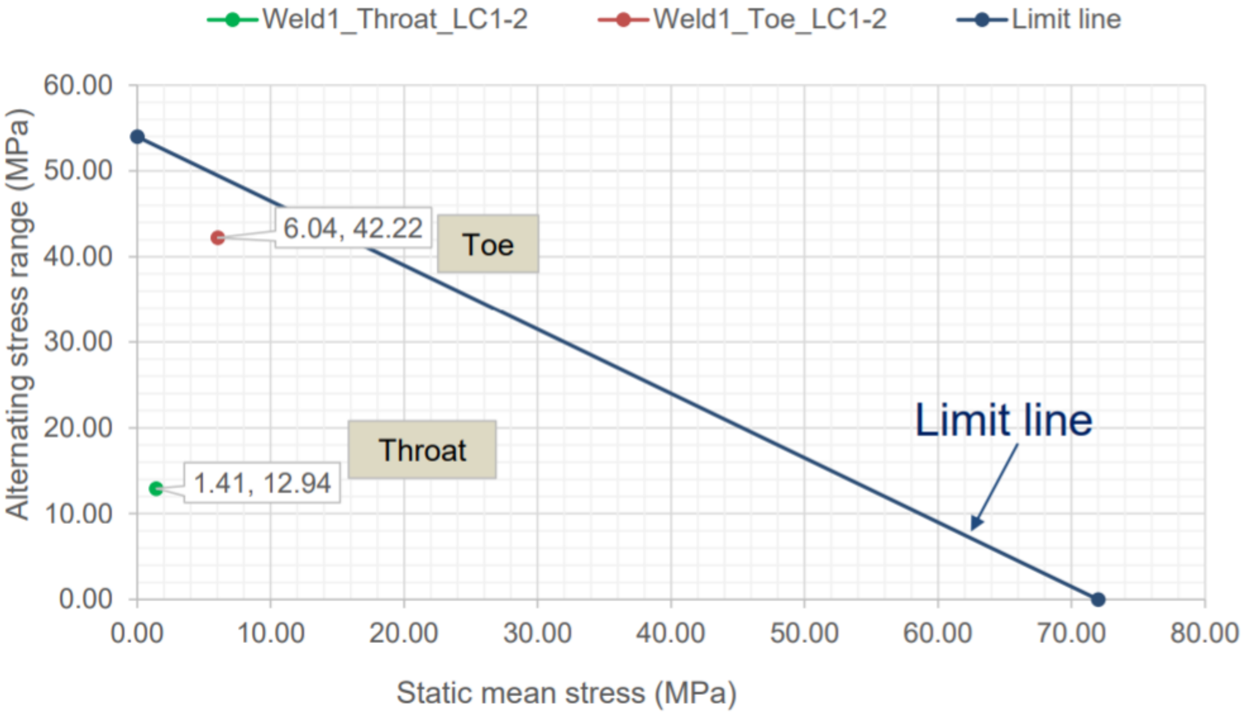
Part	Material CES	Young's Modulus (Gpa)	Poisson's Ratio (μ)	Mass Density (ρ), kg/m^3	Tensile Yield Strength (Mpa)	Tensile Ultimate Strength (Mpa)	0.4 * YTS$_{base}$ (Mpa)	0.3 * UTS$_{weld}$ (Mpa)	Mean Stress Limit	0.0003 * E (Mpa)	0.3 * YTS$_{base}$ (Mpa)	0.25* UTS$_{weld}$ (Mpa)	Alternating Stress Limit
Bracket	30176	200000	0.32	7850	230	360	92.0	-	**72.0**	60.0	69.0		**54.0**
Tube	30125	205000	0.3	7870	180	310	72.0	-		61.5	54.0		
Fillet Weld	ER 70S-6	200000	0.3	7850		400	-	120.0		60.0	-	100.0	

Weld Location 1

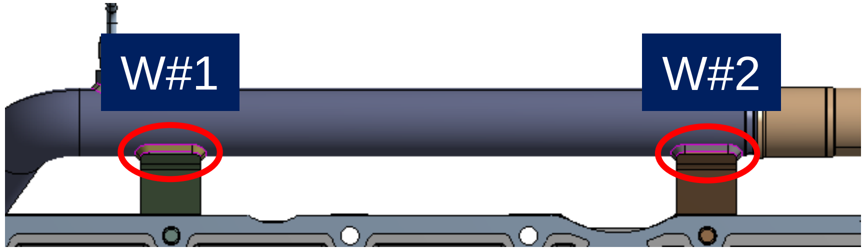
Current design

Weld Location 2



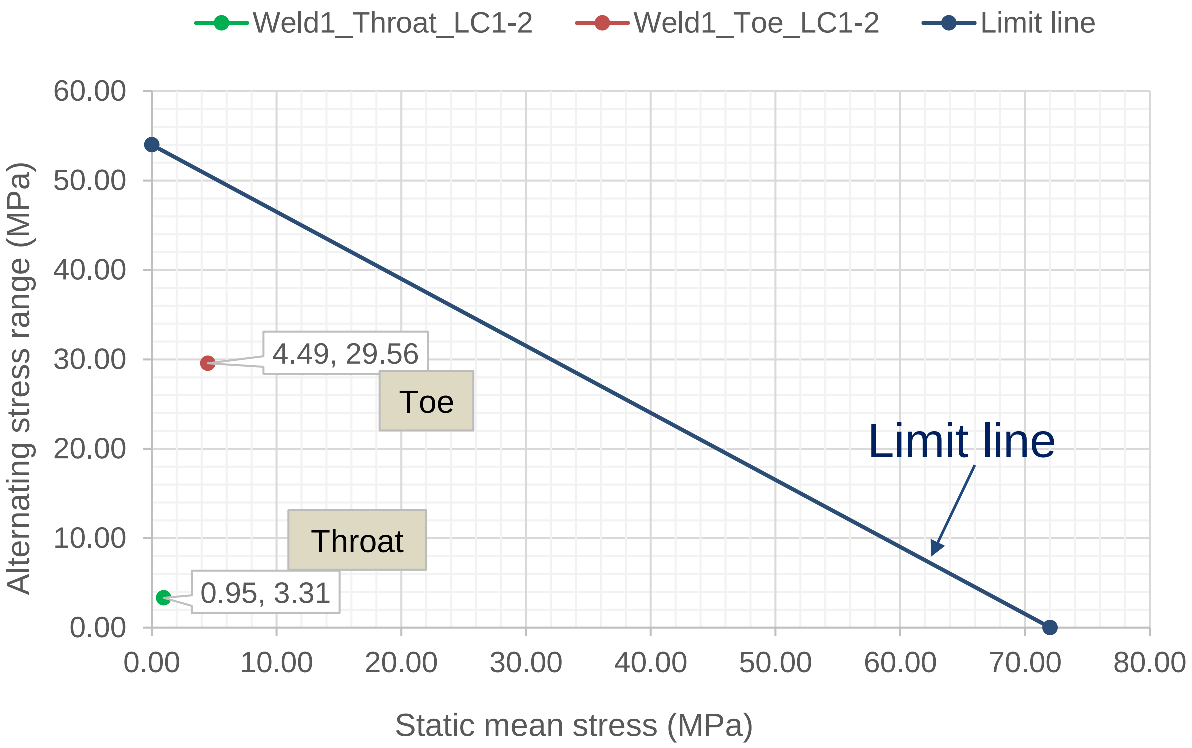


Step 3 Validation – Long Tube

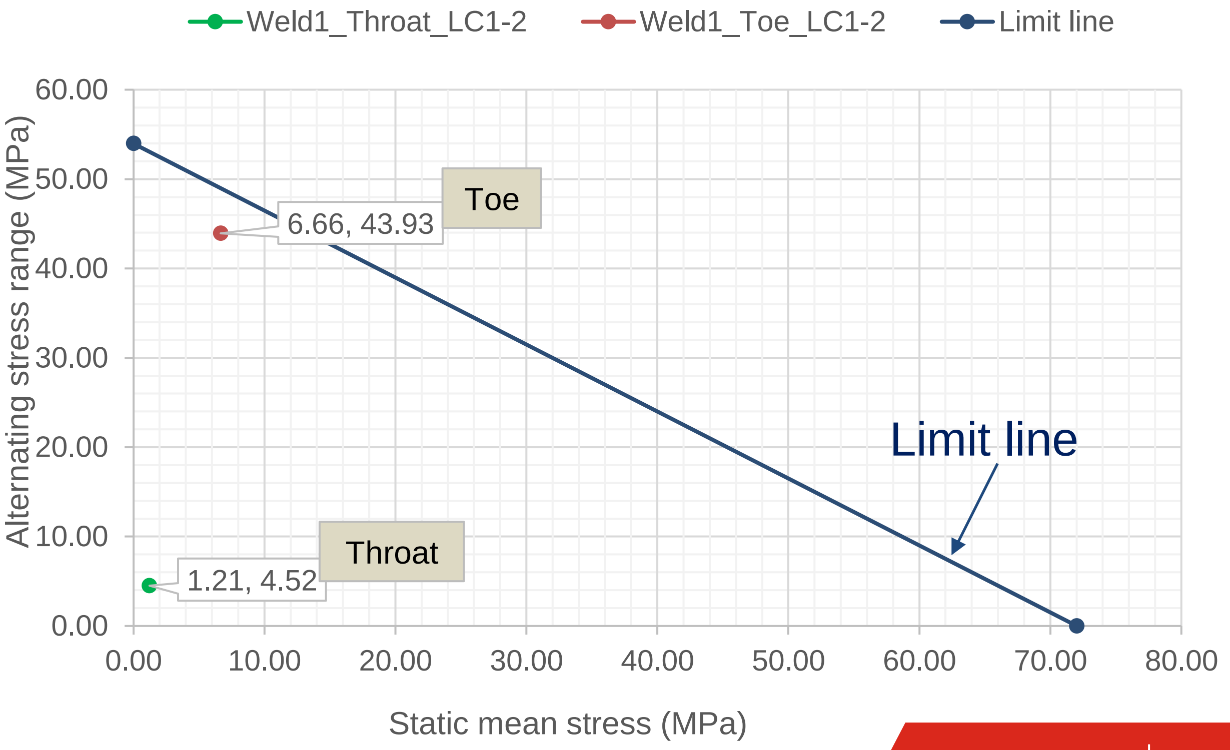


With step 3 additional weld implemented:

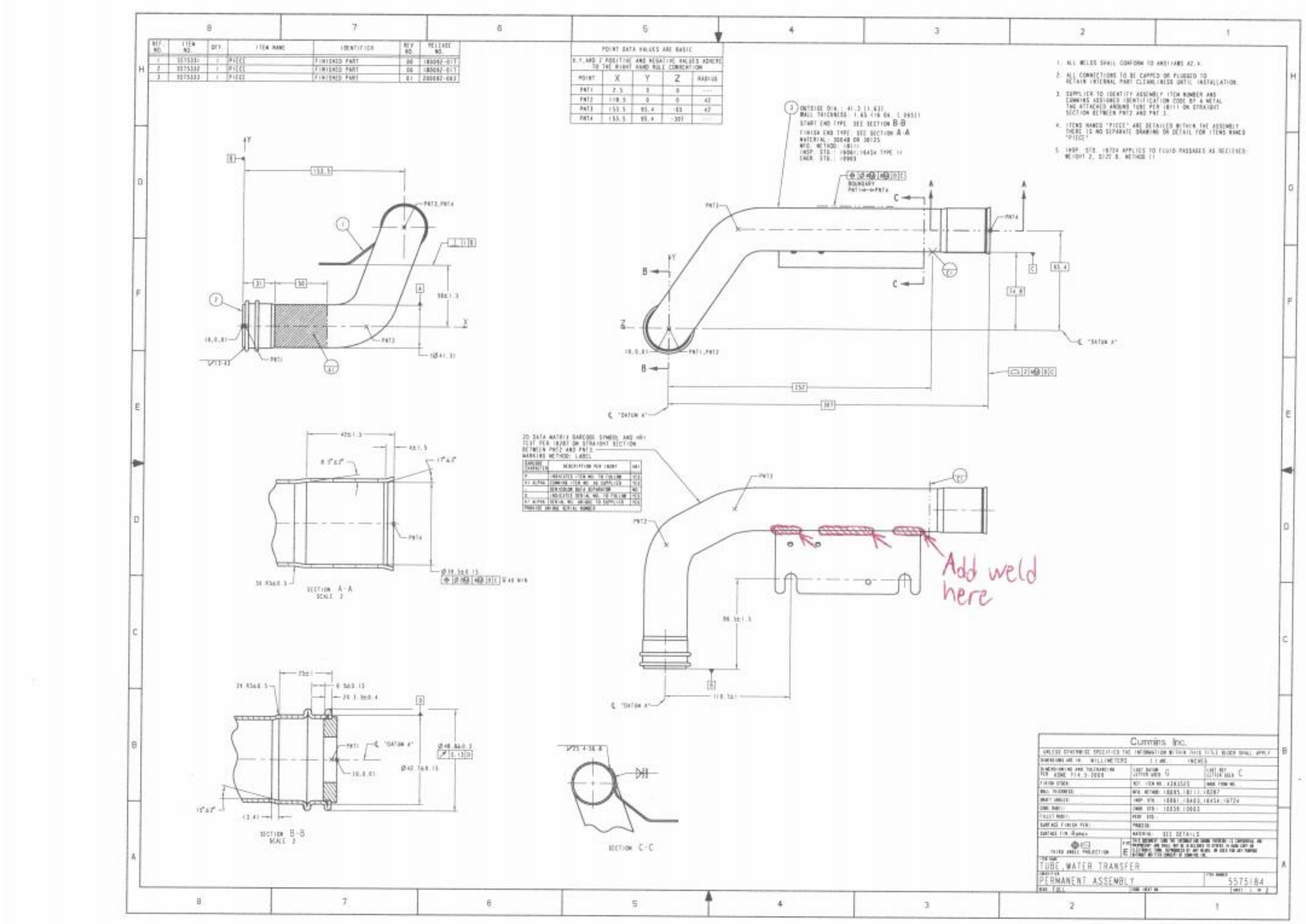
Weld Location 1

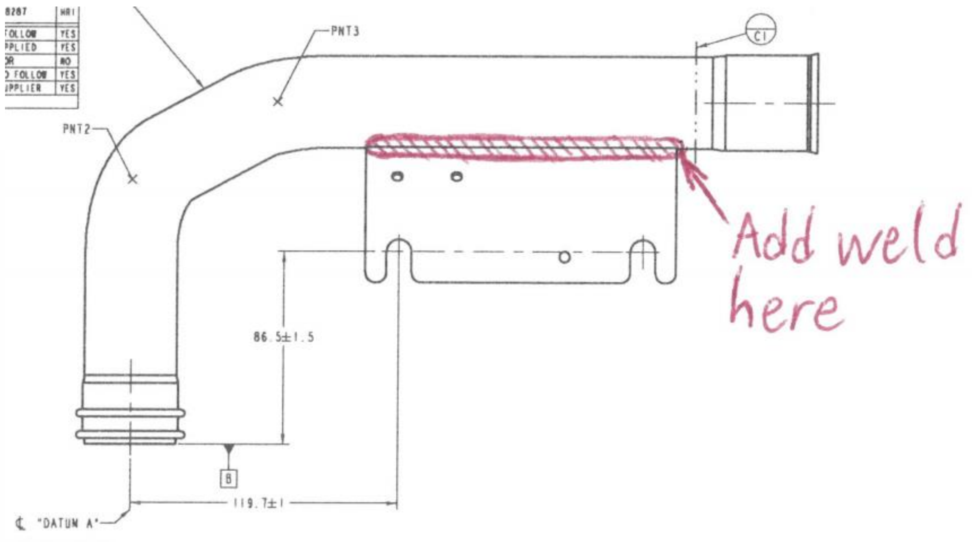


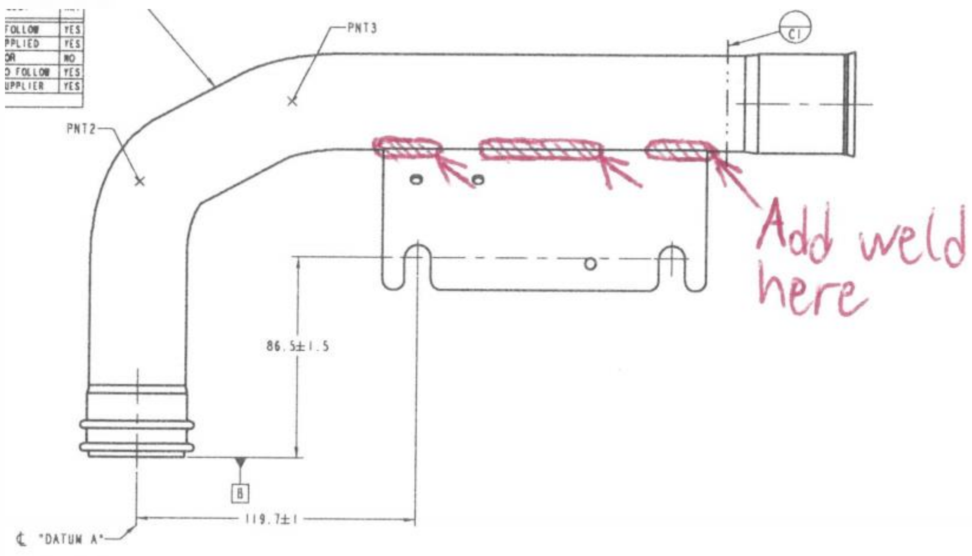
Weld Location 2



Step 3 Solution – Short Tube







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Drafter: **Michael Alan Greenwood** Date: **19MAR2020**
Checker: **Philip Flamion** Date: **02APR2020**
Approver: **Mohammed Abdul Saleem Khan**
Date: **02APR2020**

Revision: **2** State: **Released**
Change: **200092-003**

Step 3 Solution – Short Tube

- Supplier proposed an alternate method to addition of weld
  - Slot machined into the bracket and filled with weld
  - Many slot dimension options given, all found acceptable to be machined
- Chosen slot dimensions: 5/32” wide, 1” long
- This additional weld will strengthen the joint and may lead to lower stress
  - Both transfer tubes are in the same loading system
  - Similar ANSYS stress analysis conducted on this tube
  - More weld to distribute stress, less critical point stress

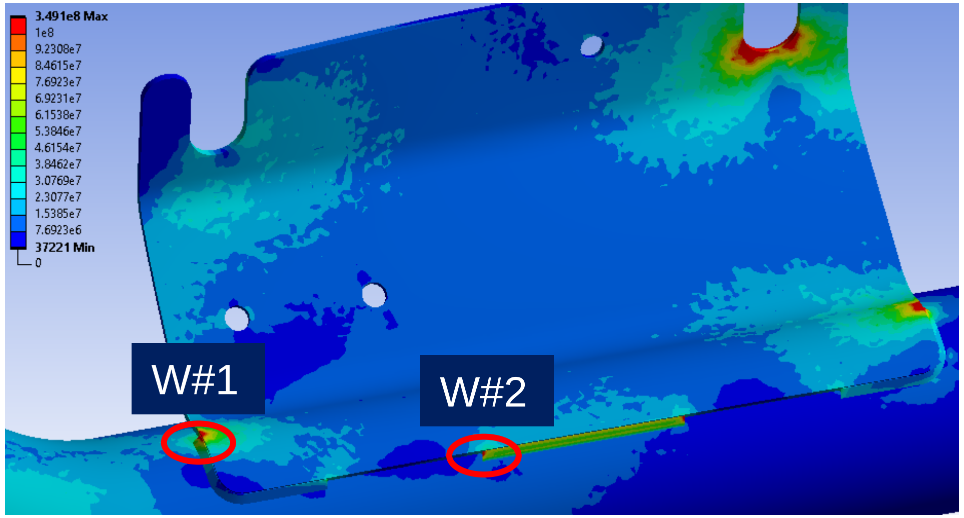
Step 3 Validation – Short Tube

- Conducted same comparative ANSYS analysis as long tube analysis on current welded joint vs additional weld
  - Evaluates the impact of the additional weld on stress within the system
- Found average stress acting upon weld toe and throat of each joint
  - Same applied force of 10G on each system for alternating stress
  - Hot spot method used to find mean stress
- Generated Goodman diagram with lowest stress limits
  - Compares level of stress acting upon joints of current design vs additional weld
  - Determines how likely each design is to experience fatigue stress

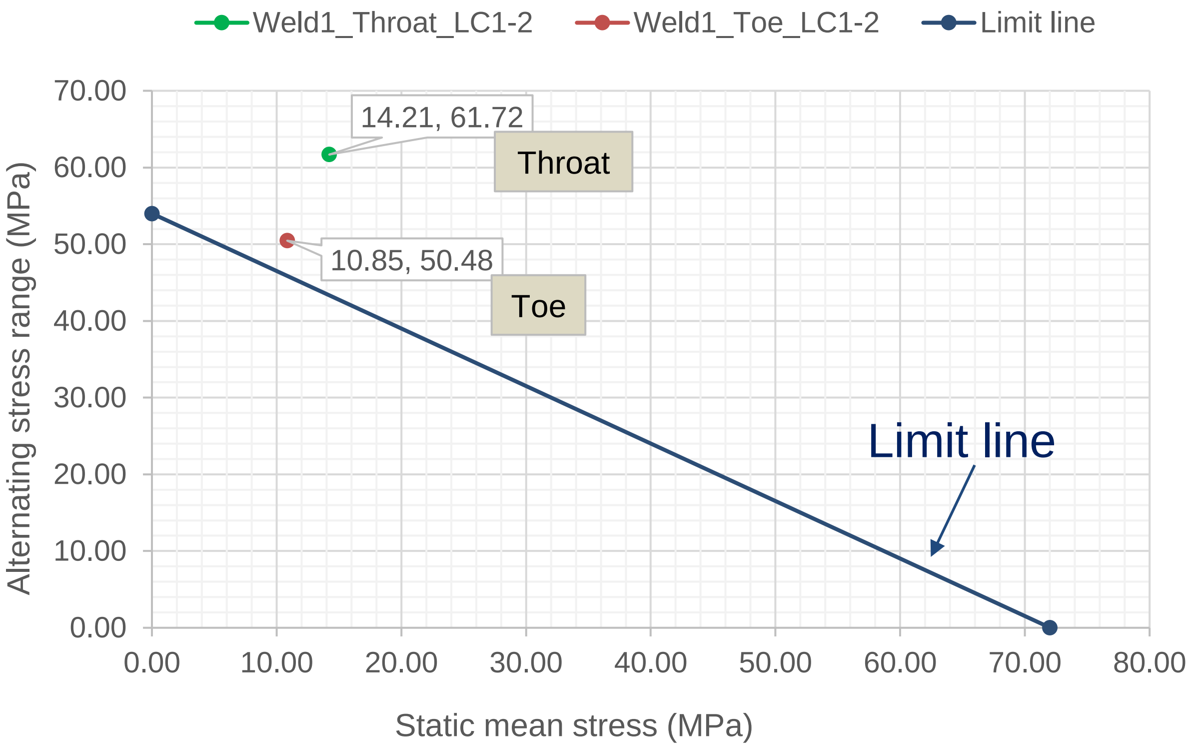
- Joints with the additional slotted weld experience **significantly less stress** and are less likely to fail due to fatigue stress

Step 3 Validation – Short Tube

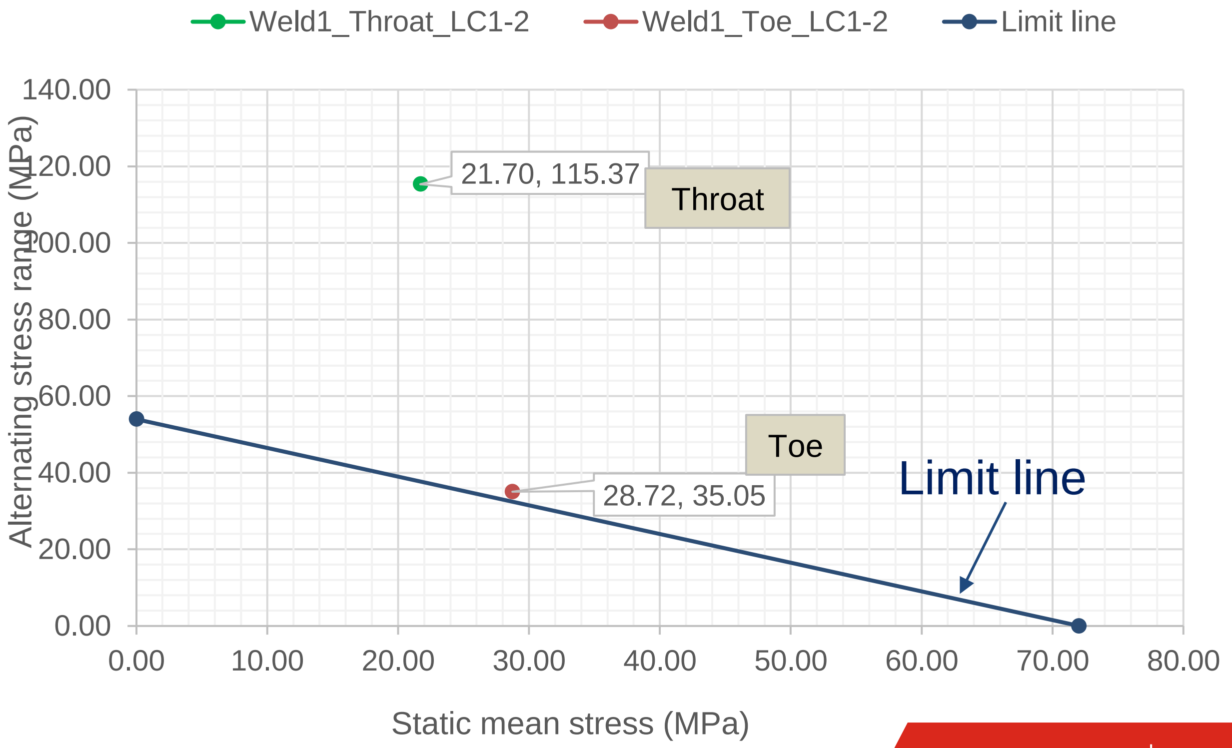
Current design:



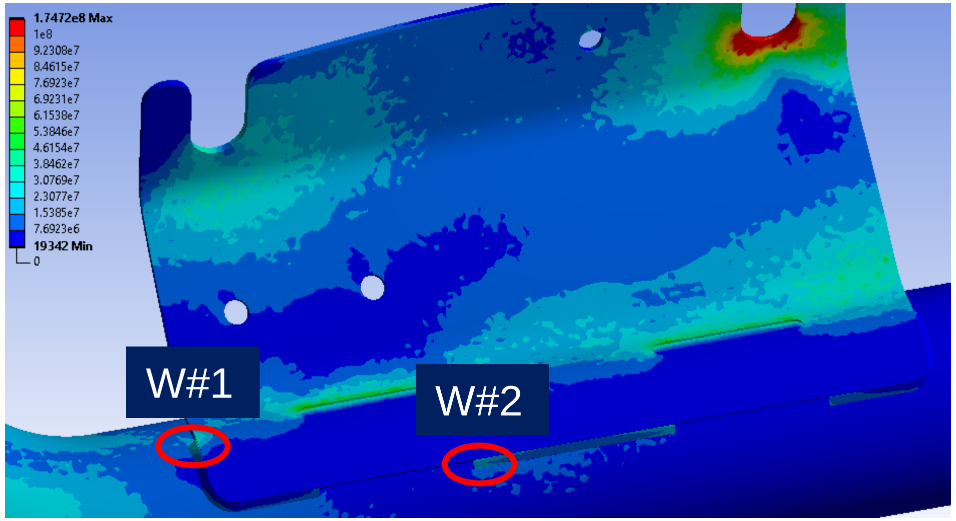
Weld Location 1



Weld Location 2

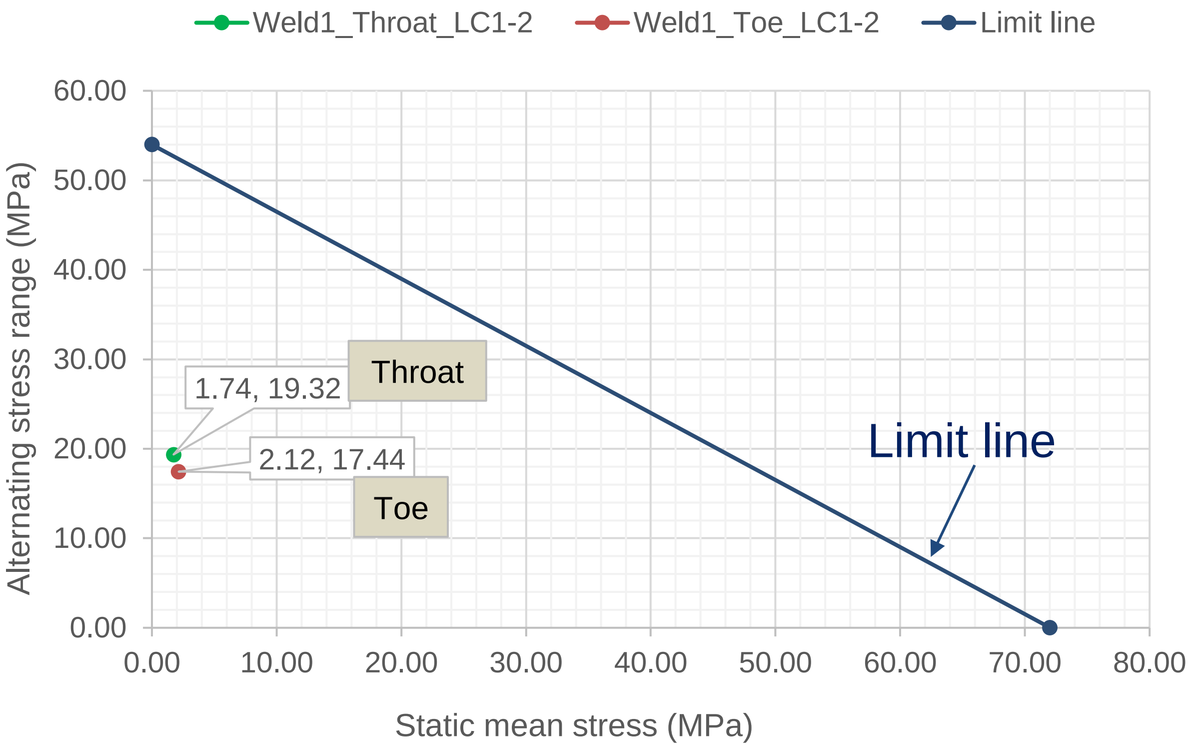


Step 3 Validation – Short Tube

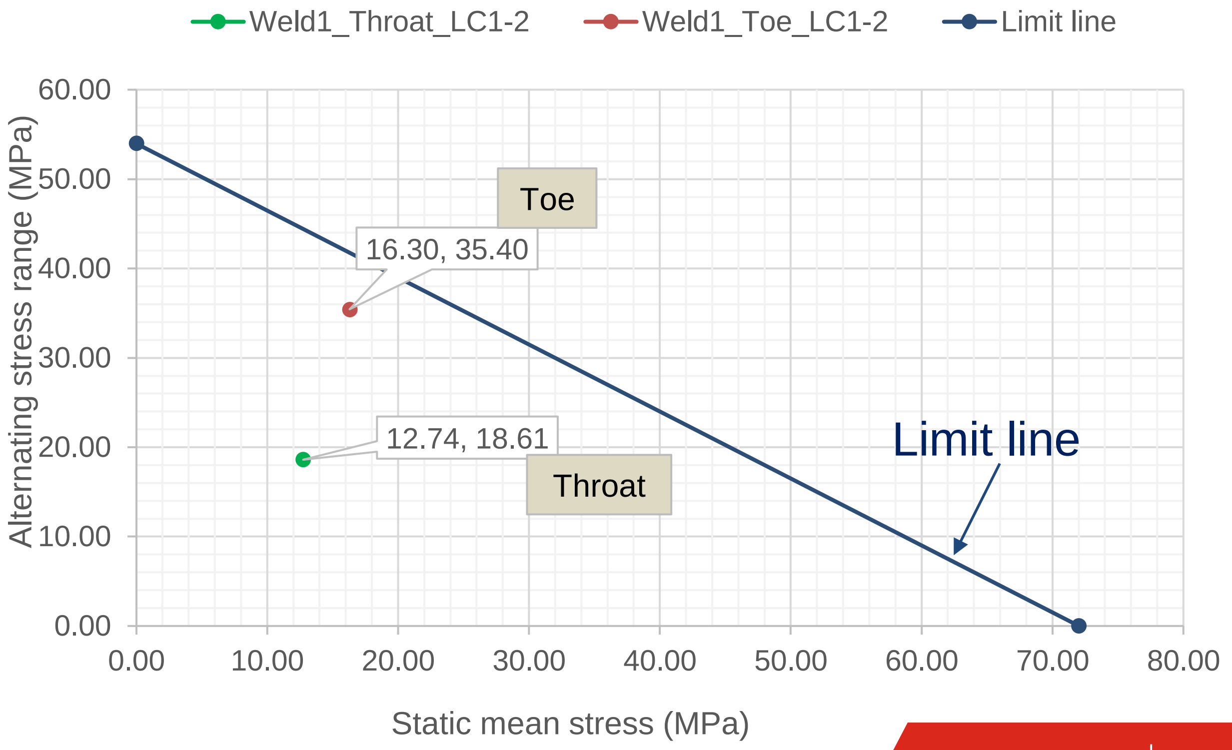


With step 3 additional weld implemented:

Weld Location 1



Weld Location 2



Solution Effective Rates

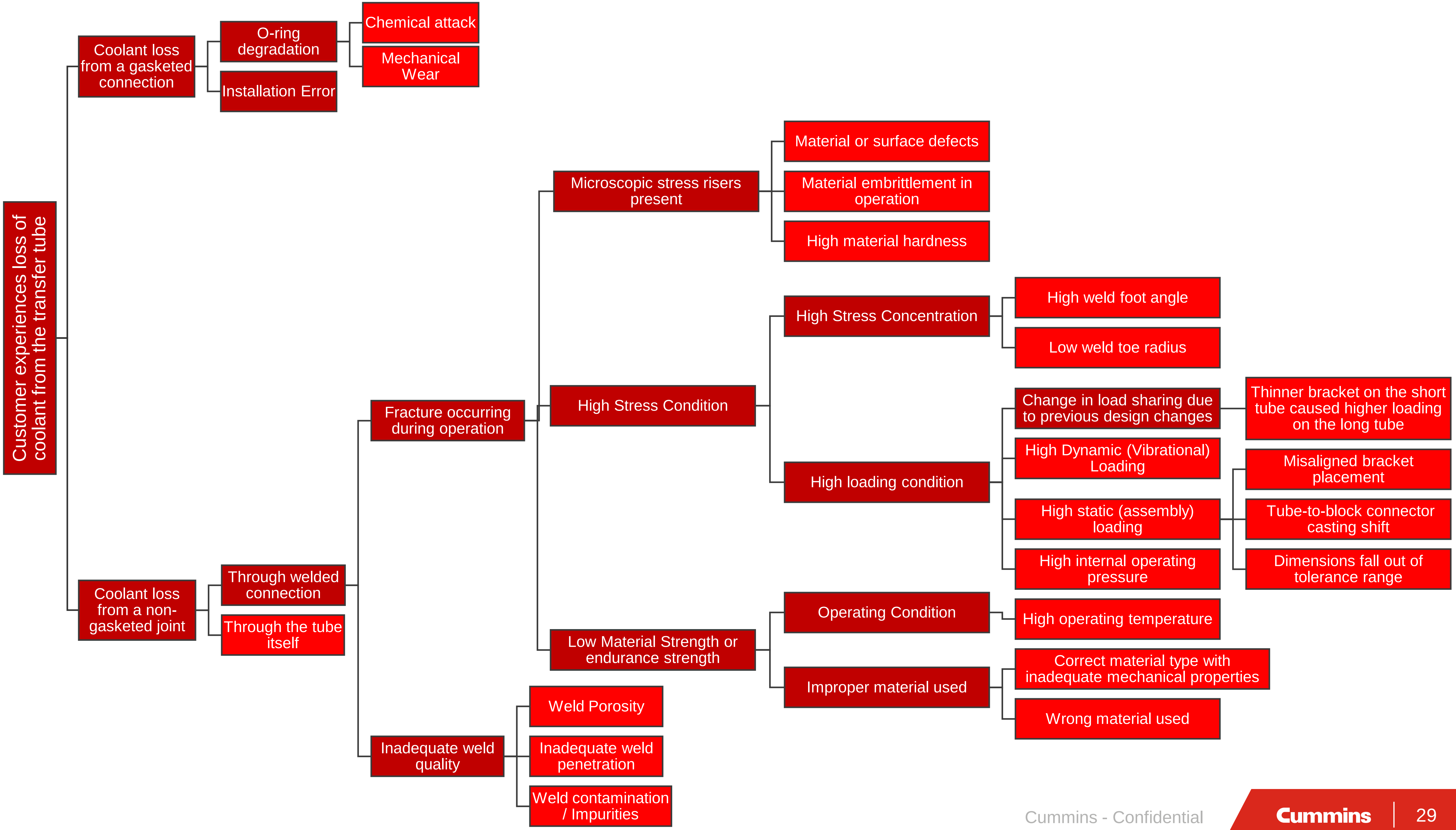
- Long tube (4367122)
  - Weld location 1 toe
    - Alternating stress reduction: 51.7%
    - Mean stress reduction: 0.22%
  - Weld location 2 toe
    - Alternating stress increase: 4.05%
    - Mean stress increase: 10.3%
- Avg alternating stress effective reduction rate = 23.8%
- Avg mean stress effective increase rate = 5.04%
- Solution effective rate = 21.1%

- Short tube (5575183)
  - Weld location 1 toe
    - Alternating stress reduction: 65.5%
    - Mean stress reduction: 80.5%
  - Weld location 2 toe
    - Alternating stress increase: 1.00%
    - Mean stress reduction: 43.2%
- Avg alternating stress effective reduction rate = 32.3%
- Avg mean stress effective reduction rate = 61.9%
- Solution effective rate = 38.9%

Cost Justification – All Regions

- 4367122 savings
  - Additional cost from supplier quote = in progress
  - Projected annual quantity: 15,364, Annual additional cost = in progress
  - Part-specific avg RPH = [redacted], avg cost per repair = $543.56, CPE = $26.38
  - Solution effective rate = 21.1% Annual savings = $85,518.79
- 5575183 savings
  - Additional cost from supplier quote = $1.35 / piece
  - Projected annual quantity: 15,364, Annual additional cost = $20,741.40
  - Part-specific avg RPH = [redacted], avg cost per repair = $537.64, CPE = $4.32
  - Solution effective rate = 38.9% Annual savings = $25,818.89
- Implement to reduce failures, evaluate other solutions from investigation
- Approximate savings, assumes direct correlation between stress and failure

Fault Tree Analysis



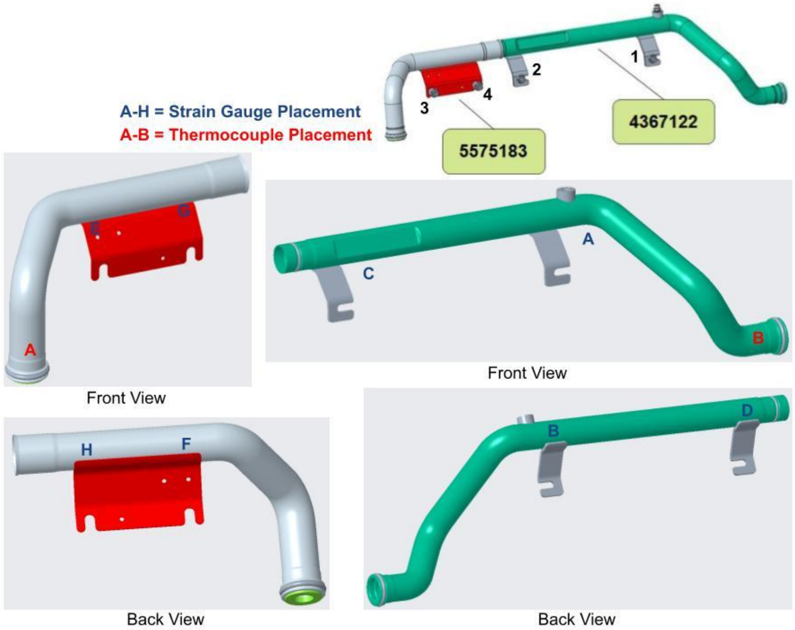
- Customer experiences loss of coolant from the transfer tube
  - Coolant loss from a gasketed connection
    - O-ring degradation
      - Chemical attack
      - Mechanical Wear
    - Installation Error
  - Coolant loss from a non-gasketed joint
    - Through welded connection
      - Fracture occurring during operation
        - Microscopic stress risers present
          - Material or surface defects
          - Material embrittlement in operation
          - High material hardness
        - High Stress Condition
          - High Stress Concentration
            - High weld foot angle
            - Low weld toe radius
          - High loading condition
            - Change in load sharing due to previous design changes
              - Thinner bracket on the short tube caused higher loading on the long tube
            - High Dynamic (Vibrational) Loading
            - High static (assembly) loading
              - Misaligned bracket placement
              - Tube-to-block connector casting shift
              - Dimensions fall out of tolerance range
            - High internal operating pressure
        - Low Material Strength or endurance strength
          - Operating Condition
            - High operating temperature
          - Improper material used
            - Correct material type with inadequate mechanical properties
            - Wrong material used
      - Inadequate weld quality
        - Weld Porosity
        - Inadequate weld penetration
        - Weld contamination / Impurities
    - Through the tube itself

Fault Validation Tasks

Location of Failure	Potential Failure Mode		Validation Tasks	Priority Rank	Status
Coolant loss through a welded connection	Stress and loading	High dynamic (vibrational) loading	Strain gauge test on transfer tubes during engine operation test	1	Finished
		High static (assembly) loading	Strain gauge test on transfer tubes connected to engine block	2	Finished
		Change in load sharing due to thinner bracket on short tube	ALD simulation of induced stress on old vs new short-tube bracket design	3	Finished
		High internal operating pressure	Coolant measurement port placement during operation test	N/A	Finished
		High stress concentration	Measure weld foot angle and weld toe radius, conduct hardness test and compare variation between points on the weld and base materials	8	Finished
	Low material strength	High operating temperature	Thermocouple measurement and coolant measurement port placement during operation test	N/A	Finished
		Wrong material used	Metallurgical inspection, hardness test on base and weld material to verify properties	14	In progress
		Correct material, inadequate mechanical properties	Tensile test, hardness test on base and weld material to verify properties	13	In progress
	Material properties	Material defects	Metallurgical inspection for surface inclusions, porosity, and discontinuous microstructure	15	In progress
		Surface defects	Metallurgical inspection for micro-cracks, rough surface, and witness marks	16	In progress
		Material embrittlement in operation	Metallurgical inspection for evidence of material embrittlement - Grain boundary oxidation and hydrogen embrittlement	17	In progress
		High material hardness	Hardness test - compare hardness of failed samples to maximum print hardness specification and minimum material hardness specifications	6	Finished
	Dimensional quality	Misaligned bracket placement	Gauge lab measurement of failed samples to determine position of bracket	10	Finished
		Tube-to-block connector casting shift	Identify tube-to-block connectors with bolt holes outside of tolerance range, determine how frequently these quality-issue connectors are produced, include these faulty connectors in a strain gauge test, and compare with initial strain gauge results	11	Finished
		Dimensions fall out of tolerance range	Measure dimensions of failed samples that have an affect on the placement and assembly of the transfer tubes - determine if any fall outside of the print tolerance range	12	Finished
	Weld quality	Weld porosity	Visual inspection of weld surface and cross-section	5	Finished
		Inadequate weld penetration	Visual inspection of weld surface and cross-section	4	Finished
		Weld contamination / Impurities	Visual inspection of weld surface and cross-section, hardness test	9	Finished
		High weld foot angle, low weld toe radius	CMM measurements of new and failed parts to compare weld foot angle and toe radius	7	Finished
Coolant loss through a gasketed connection		O-ring degradation due to chemicals	Visual inspection of failed sample O-rings	N/A	Need failed samples
		O-ring degradation due to mechanical wear	Visual inspection of failed sample O-rings	N/A	Need failed samples
		Installation error	Find location of leak, inspect connection between tubes	N/A	Not in progress
Coolant loss through the tube itself			Dye pen testing of base tube material for multiple failed samples	N/A	Need failed samples

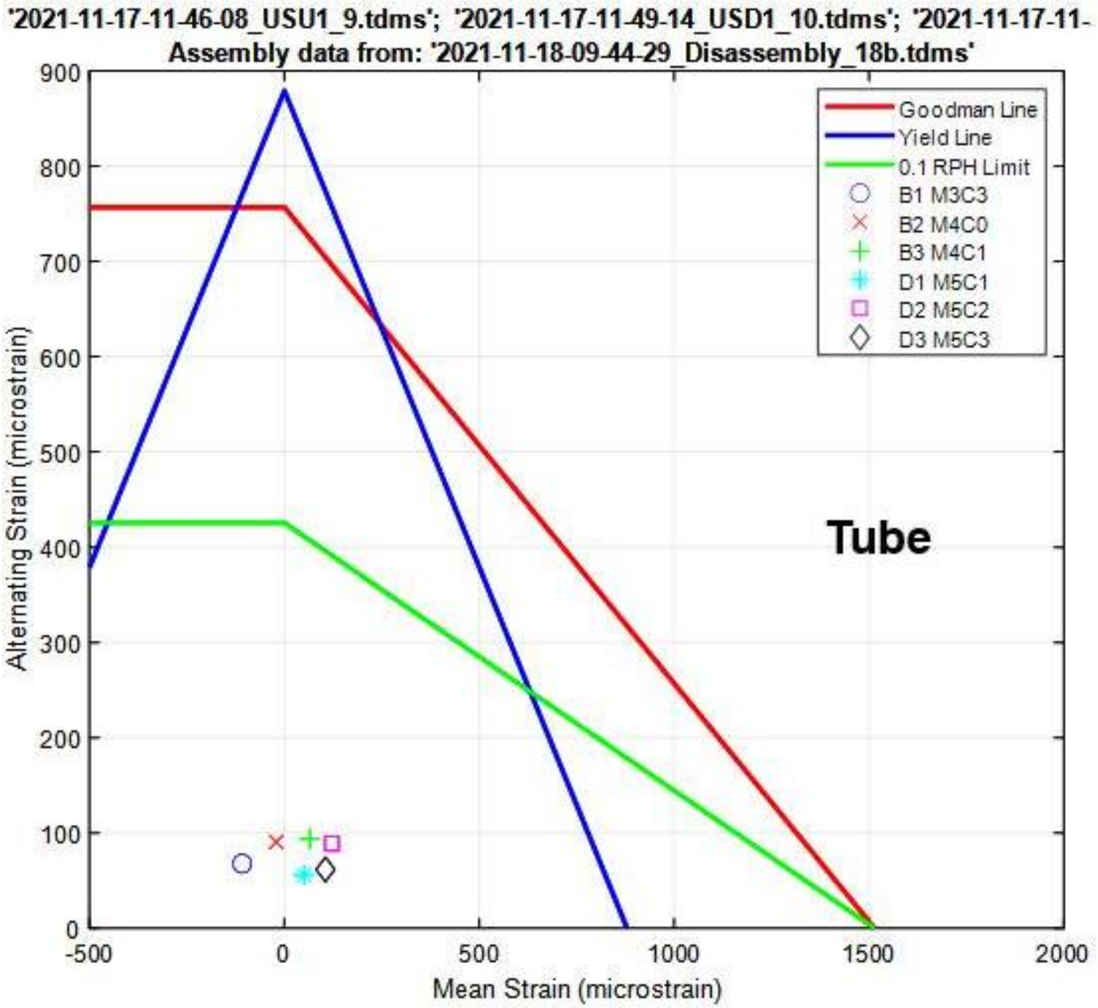
Fault Validation – High Stress Condition

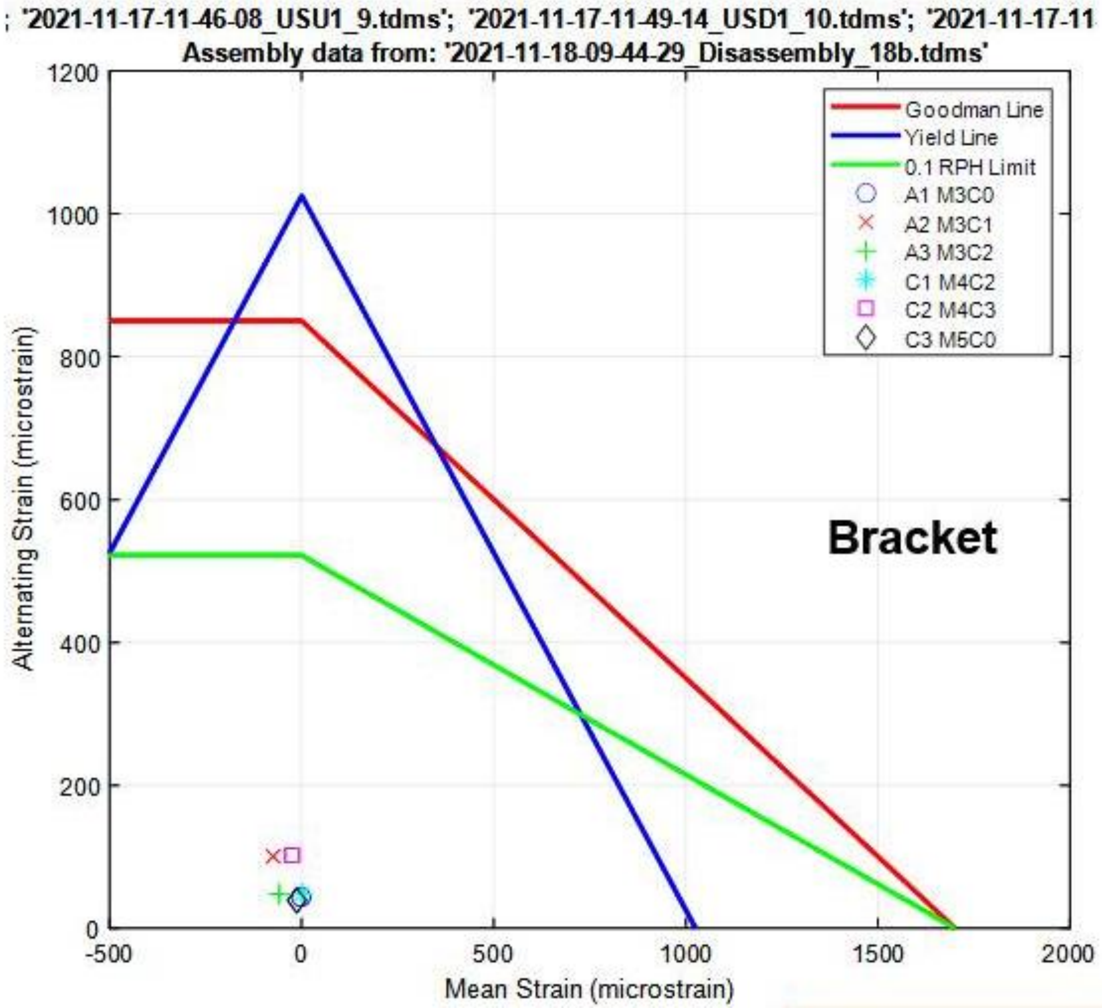
Static (Assembly) and Dynamic (Vibrational) Stress



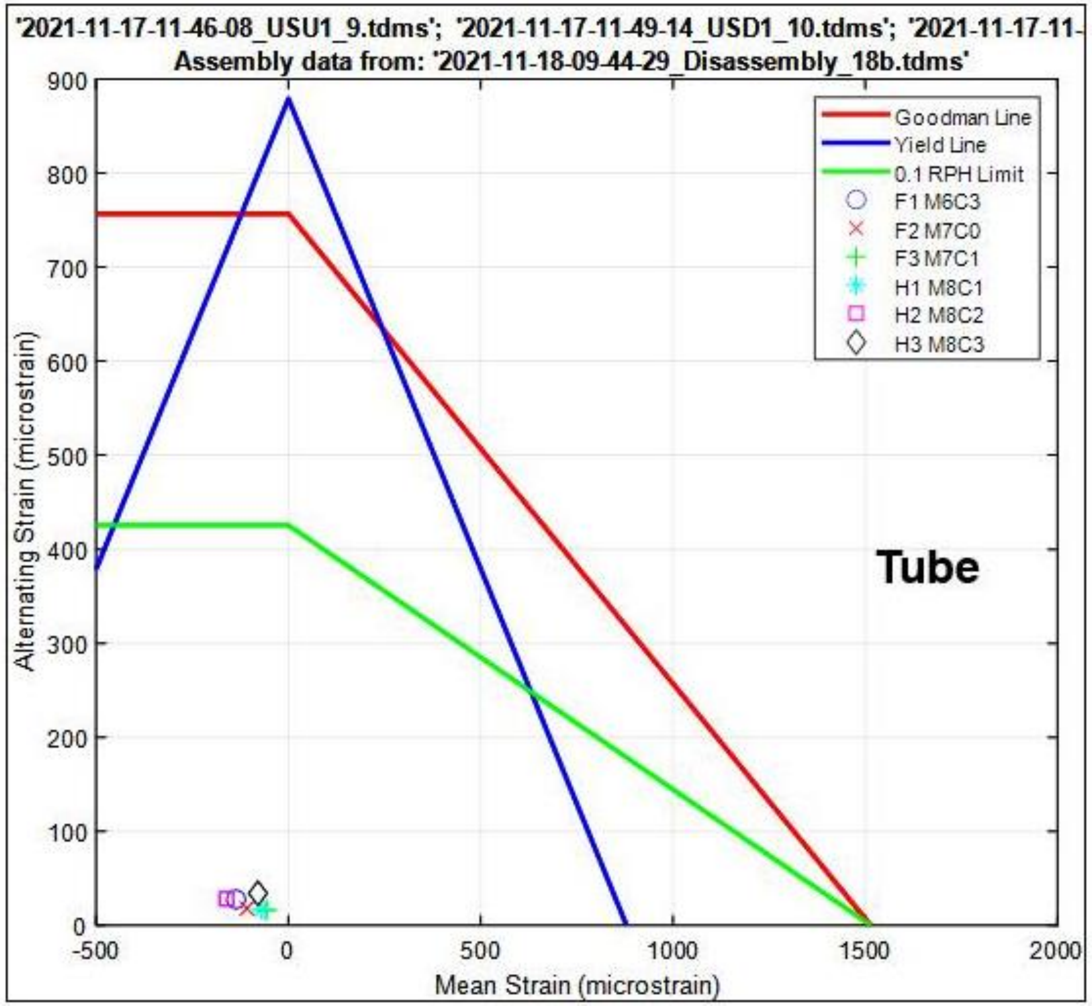
- Conduct a strain gauge test during engine operation
  - Measure transfer tubes, confirm in-spec dimensions
  - Place strain gauges on transfer tubes at these points:
  - Assemble tubes to engine and record static stress
  - Run operation test for 1.5 hours, gather strain data
    - 2 loaded and 2 unloaded sweeps
    - Low idle, high idle
  - Record critical points of stress due to vibration
    - Maximum and minimum values
- Actual static or dynamic stress on joints must not exceed allowable stress
  - If they do, excess assembly or vibrational stress is a likely failure mode
- Evaluate fatigue stress with results from static and dynamic stress tests on a Goodman diagram

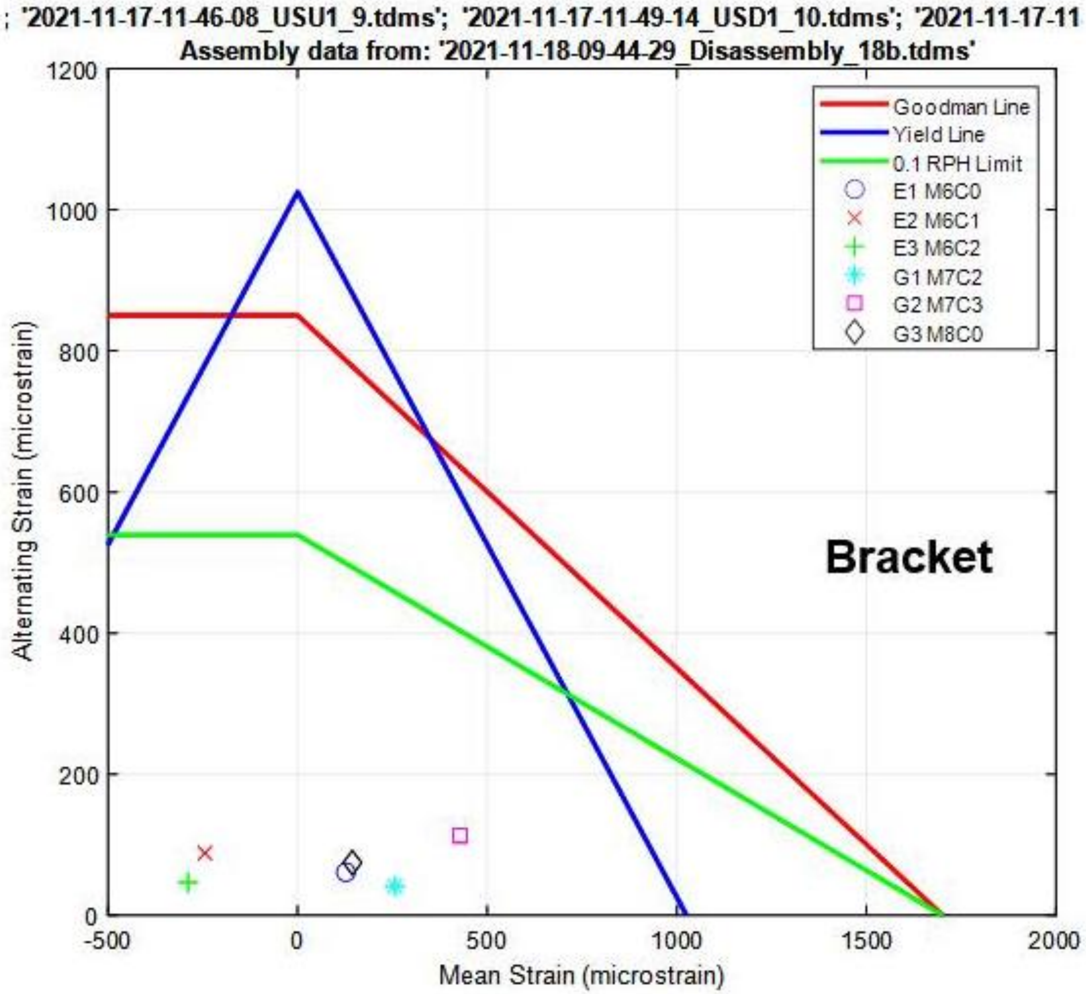
4367122 Goodman Diagrams





5575183 Goodman Diagrams





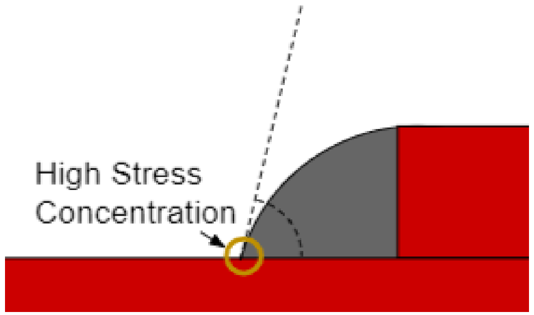
Conclusions

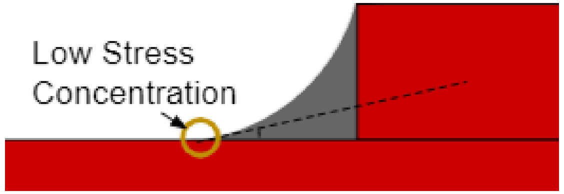
- Mean, alternating, and assembly stress on the welded joint are all minimal
- Stress may rise in uncommon circumstances, high RPH and 7th mode, but still does not exceed Goodman line
- Dimensional disparities may cause higher assembly stress and impact alternating stress
- Therefore, high static or dynamic stress are **unlikely** failure modes for dimensionally in-spec transfer tubes

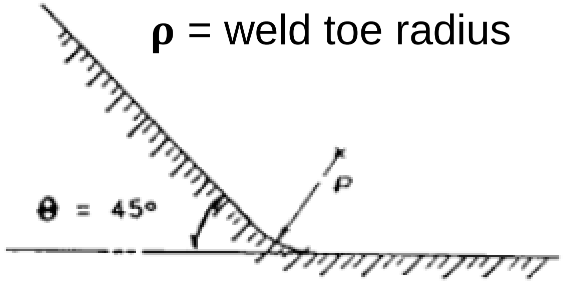
Fault Validation – Changes in Load Sharing

High Stress Concentration

- Leads to low component strength, fracture
- Theoretical causes of high stress concentration
  - High weld foot angle / convex geometry
  - Low weld toe radius
- Observe welds of failed samples and compare to non-failed samples
- Stress concentration can be approximated with the results of our hardness test
  - High hardness difference between nearby points = high stress concentration
- Conduct comparative ANSYS modal analysis
  - Convex, concave, and flat welds
  - No weld toe radius created



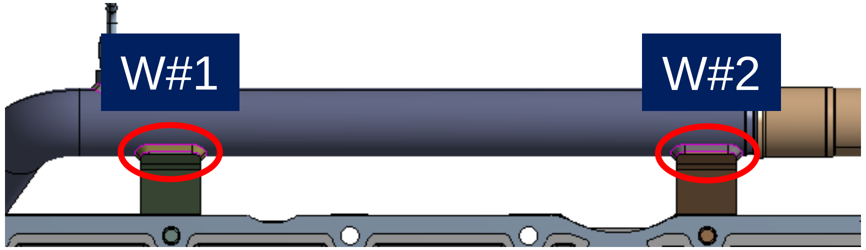




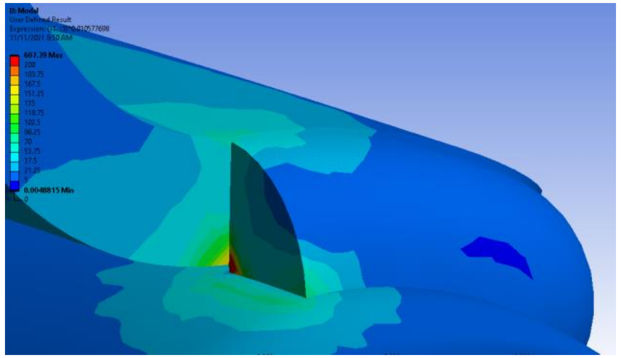
ρ = weld toe radius

Source: *Analysis of weld toe radius effects on fatigue weld toe cracks* by H.L.J Pang, Figure 2

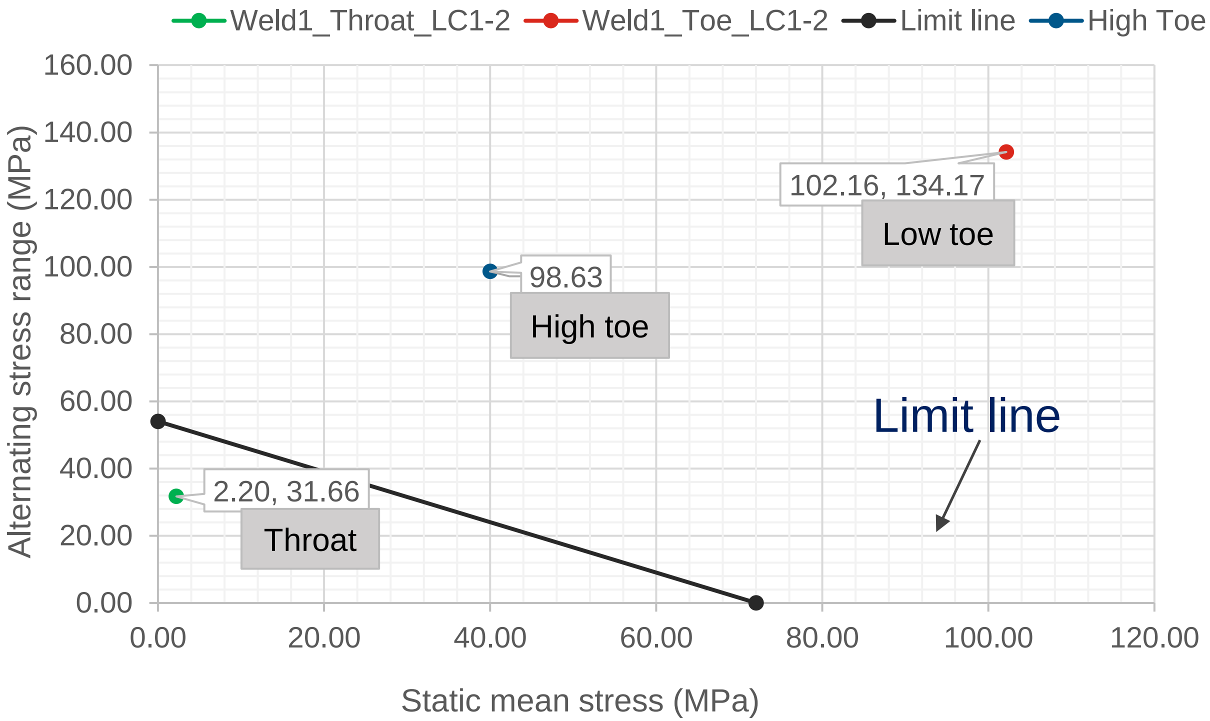
High Stress Concentration



Long tube convex weld:



Weld Location 1



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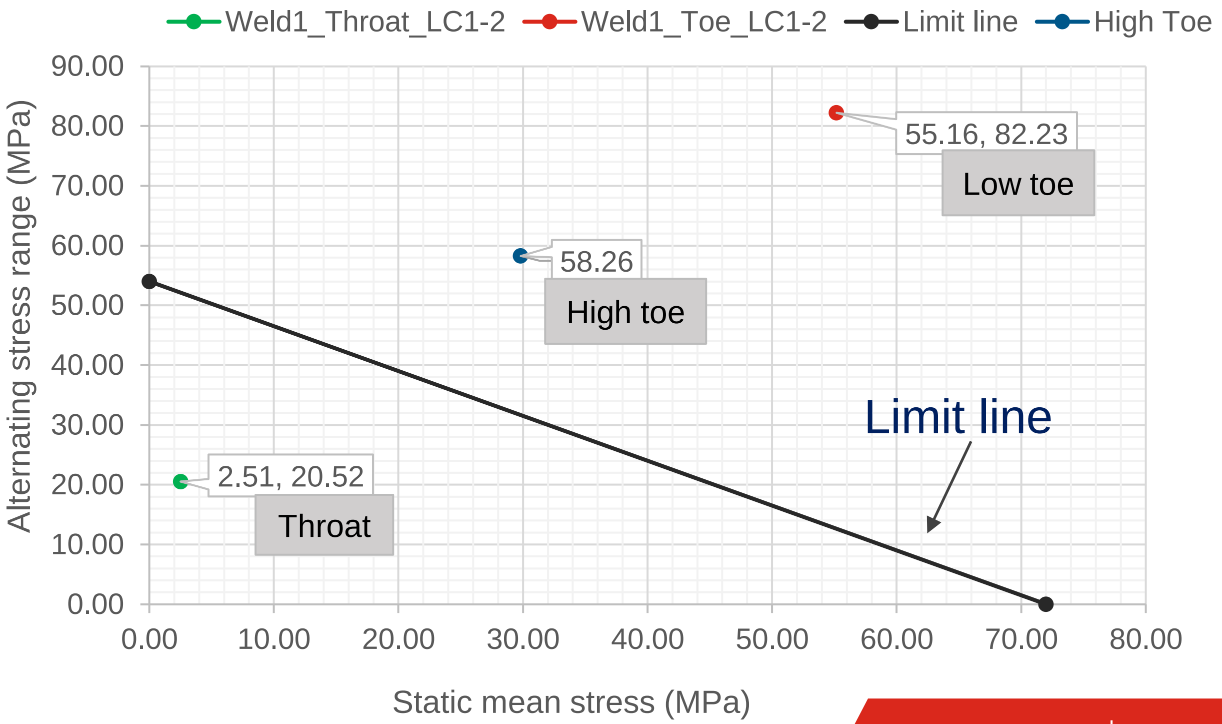
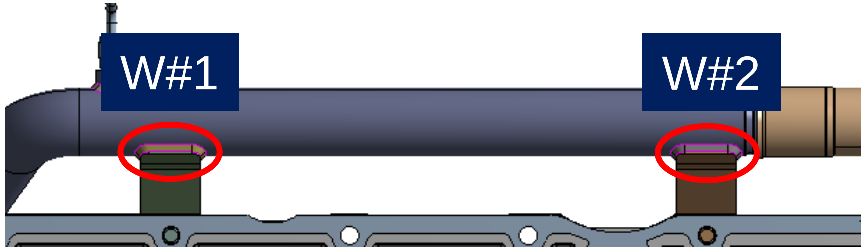
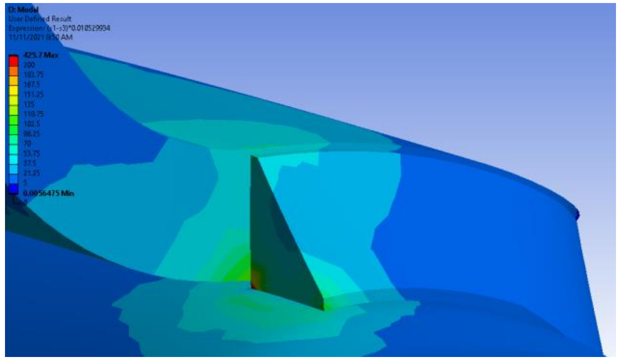


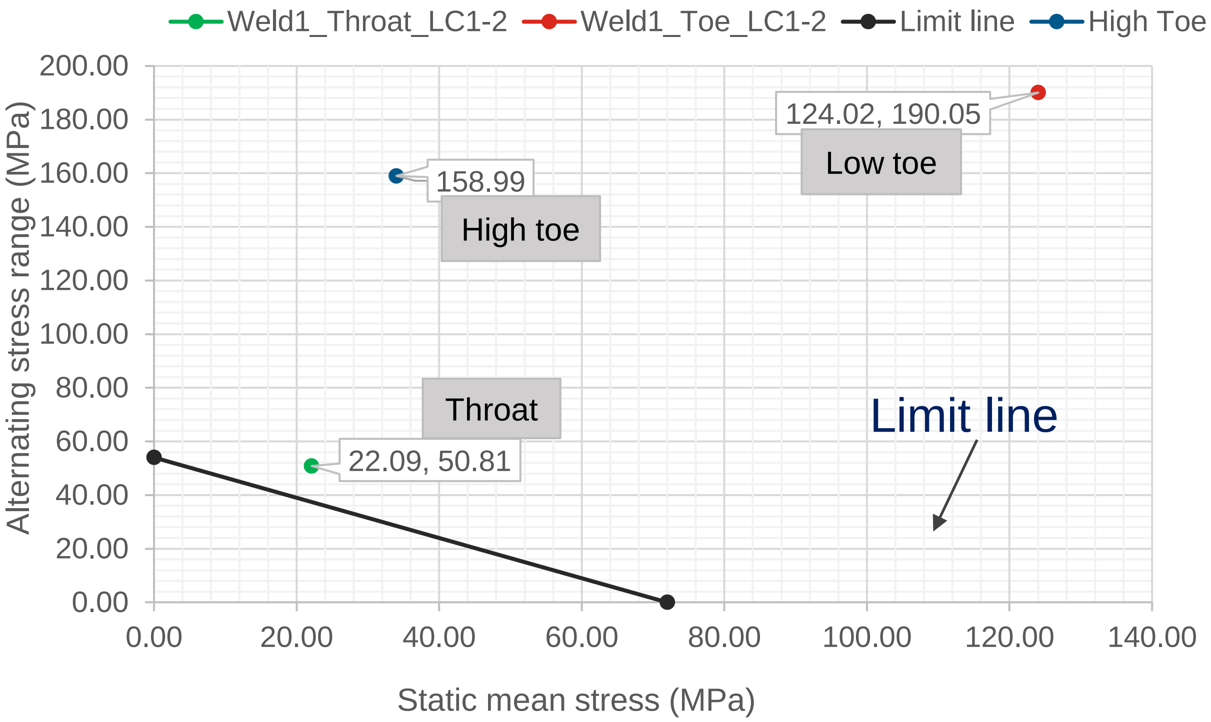
High Stress Concentration



Long tube flat weld:



Weld Location 1



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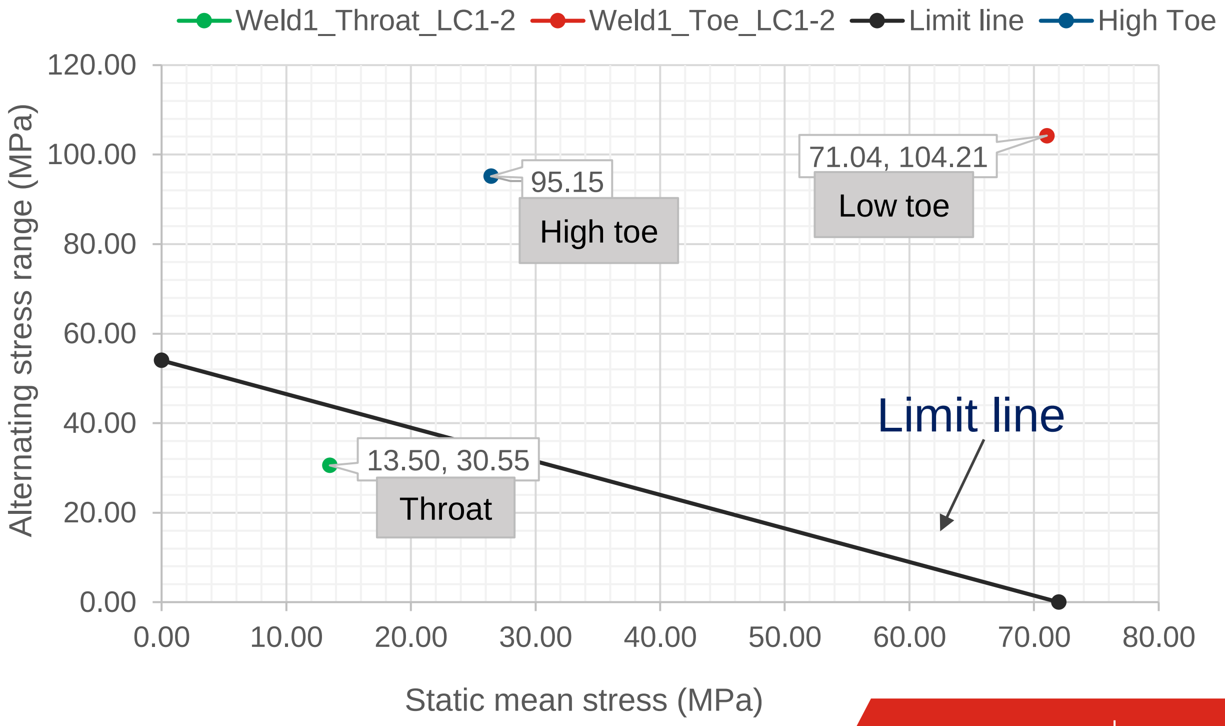
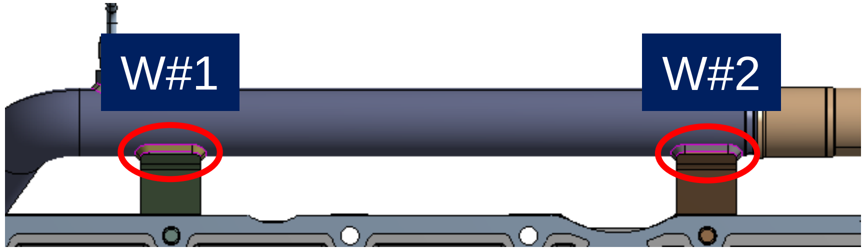
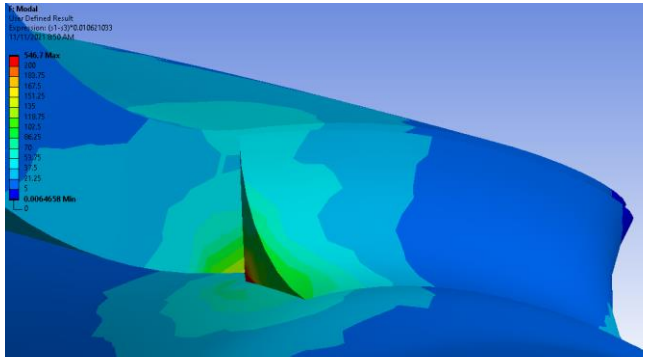


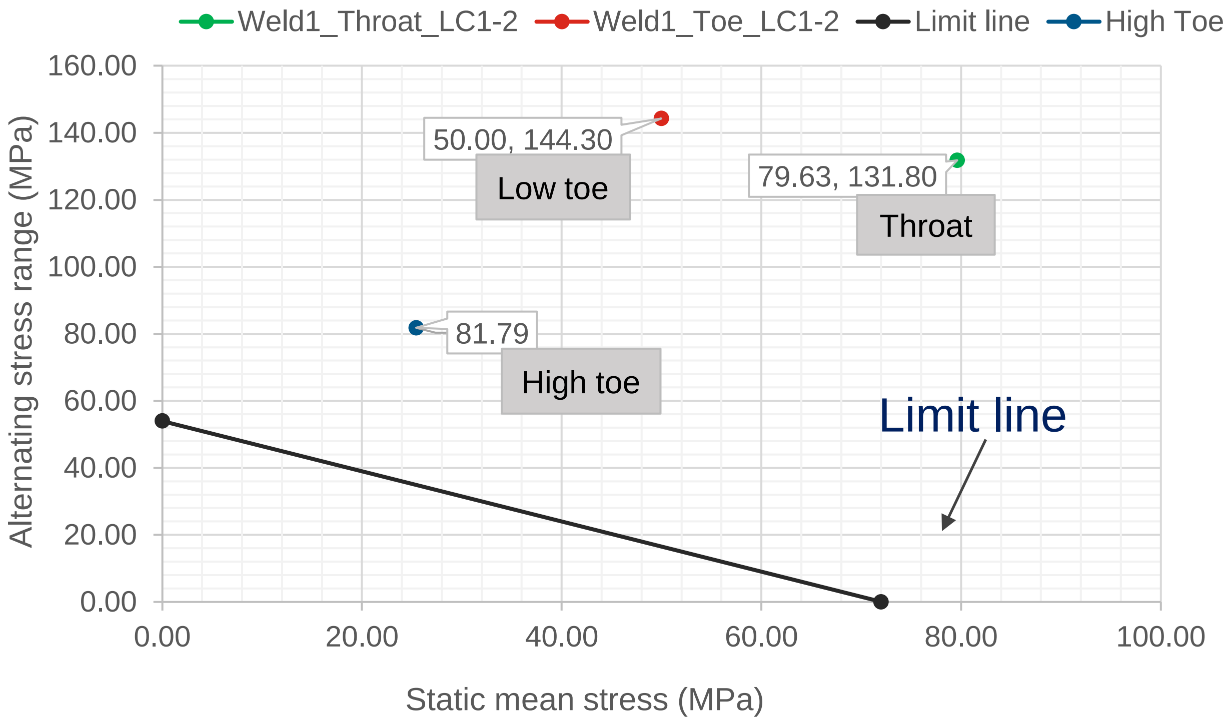
High Stress Concentration



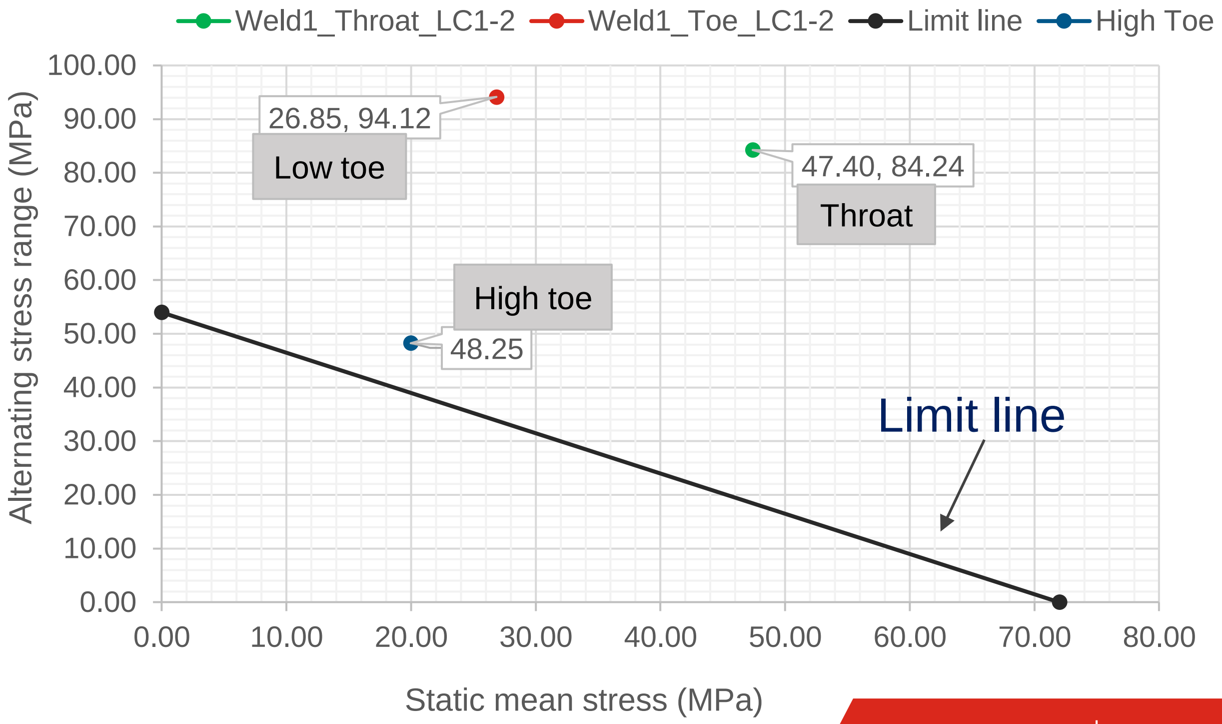
Long tube concave weld:



Weld Location 1



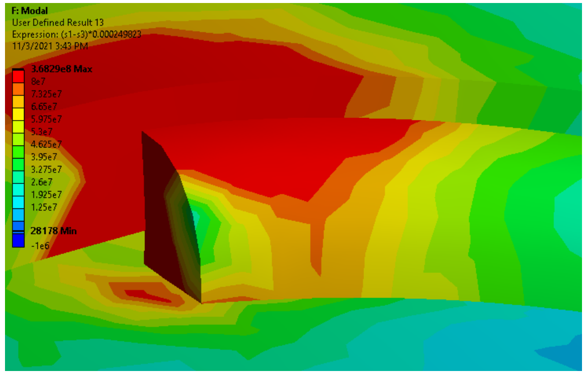
Weld Location 2

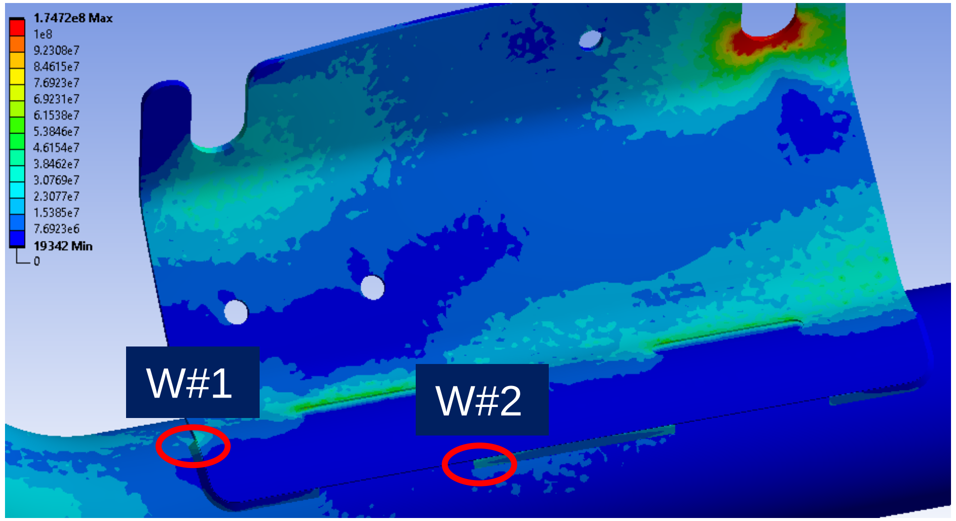


High Stress Concentration

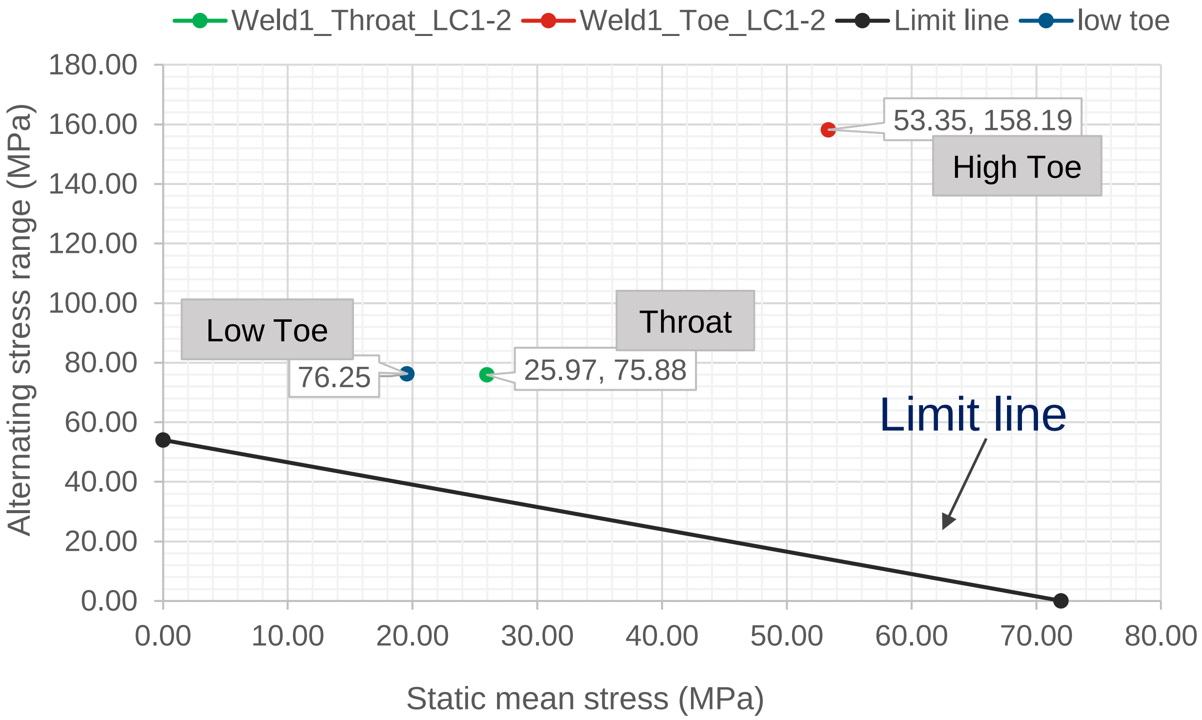
Short tube convex weld:

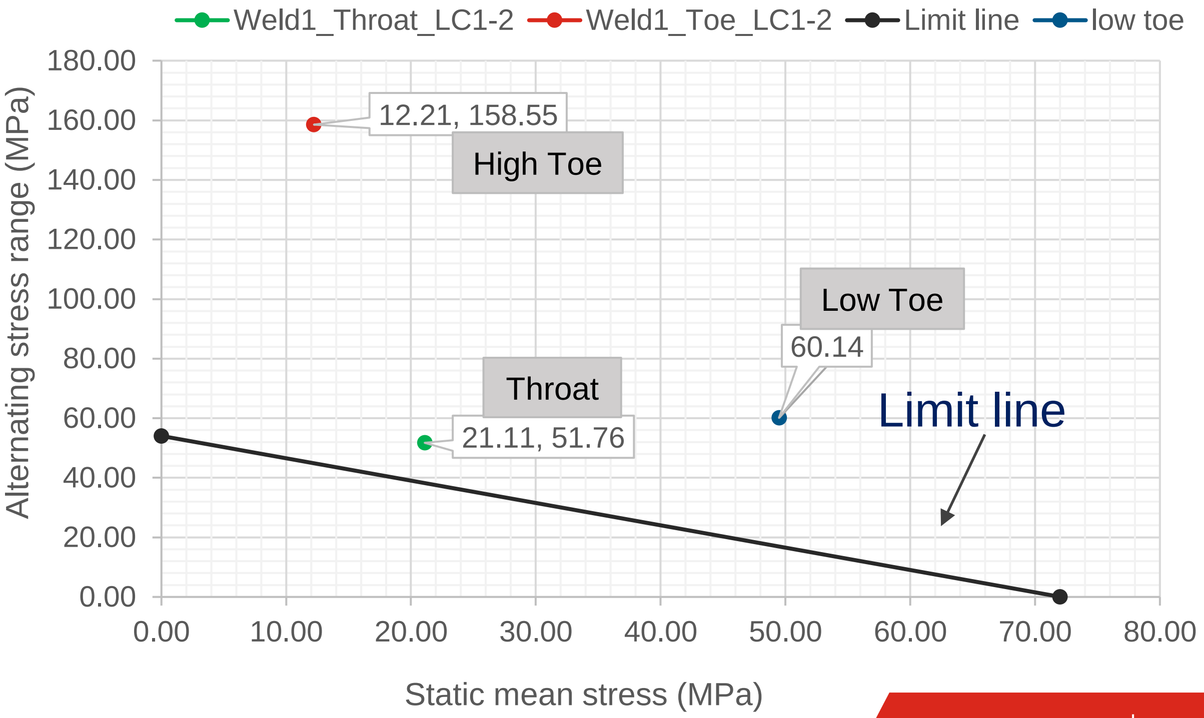
Weld Location 1





Weld Location 2

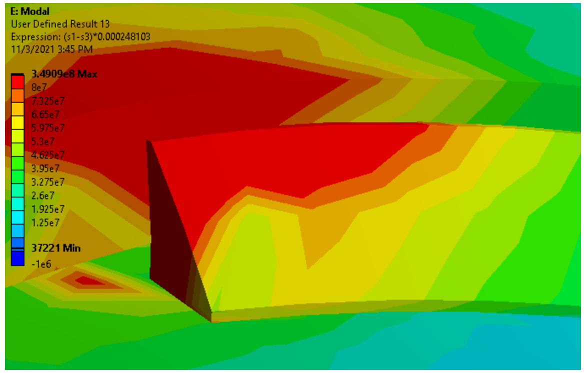


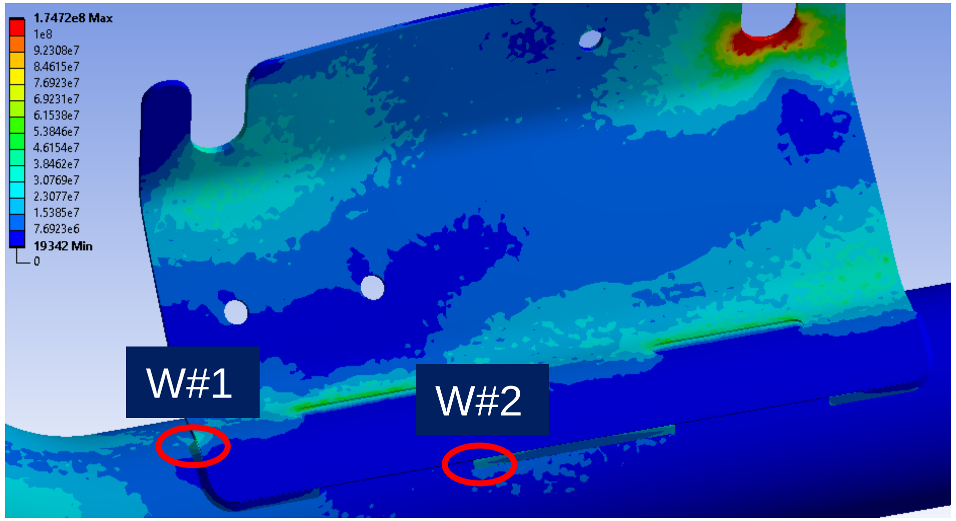


High Stress Concentration

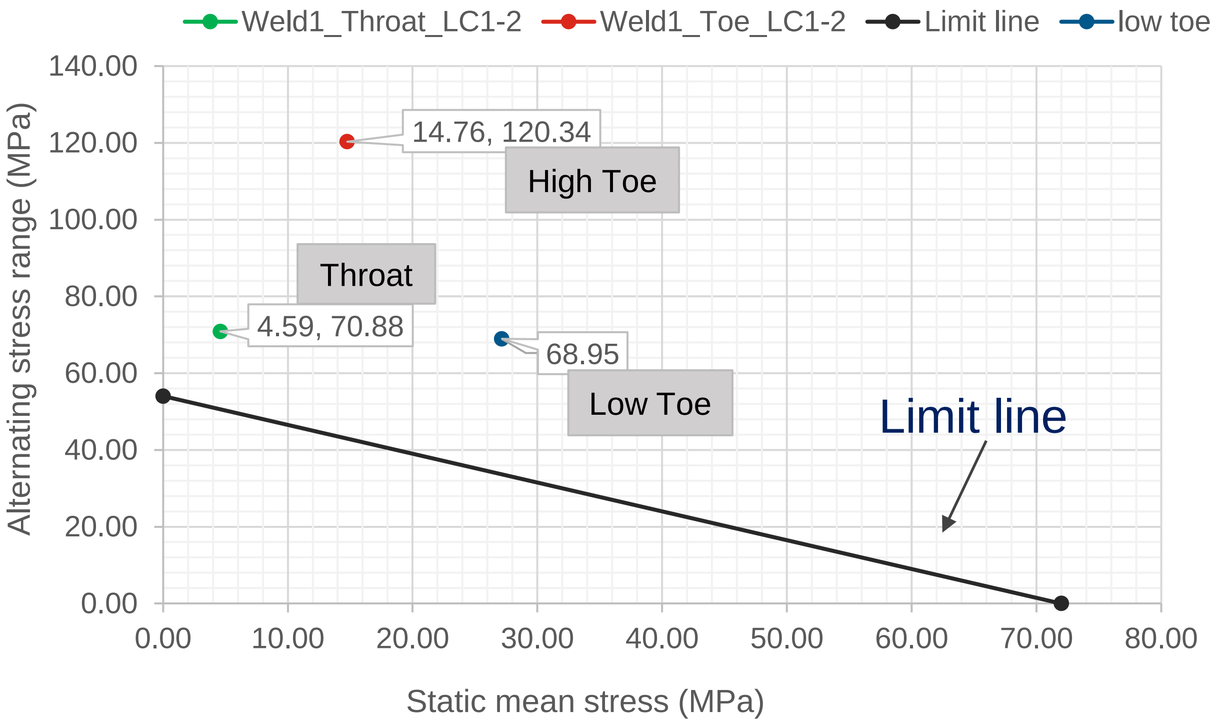
Short tube flat weld:

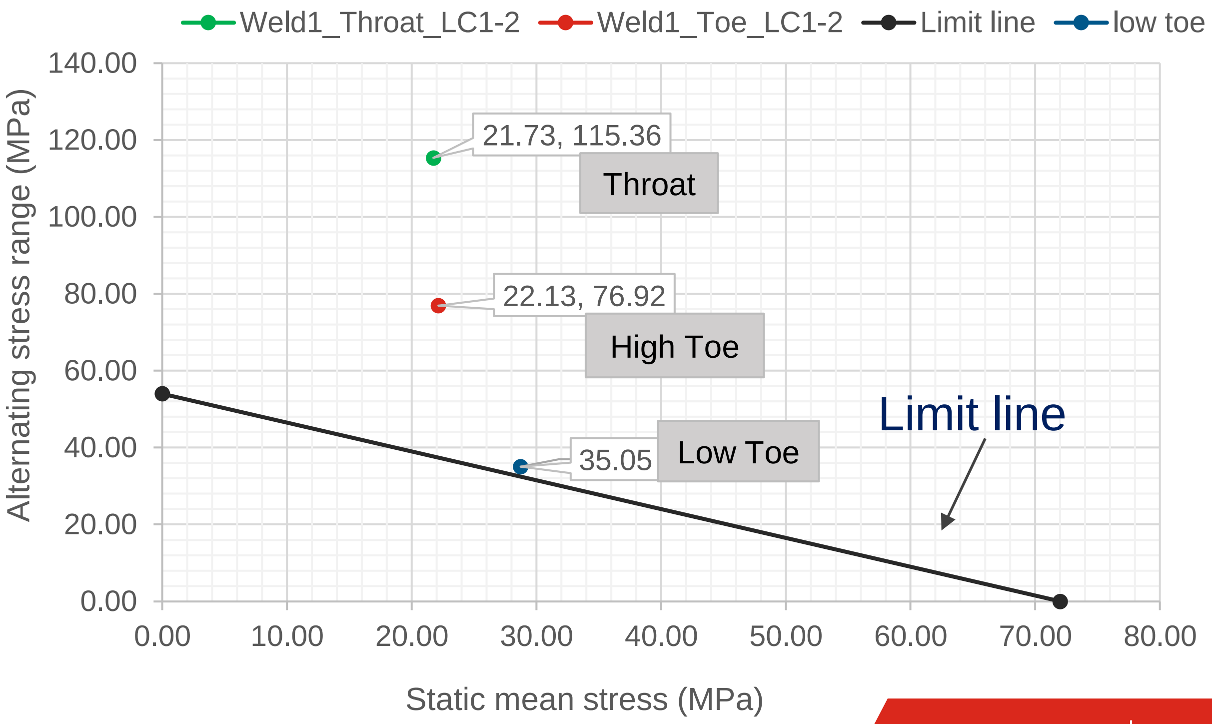
Weld Location 1





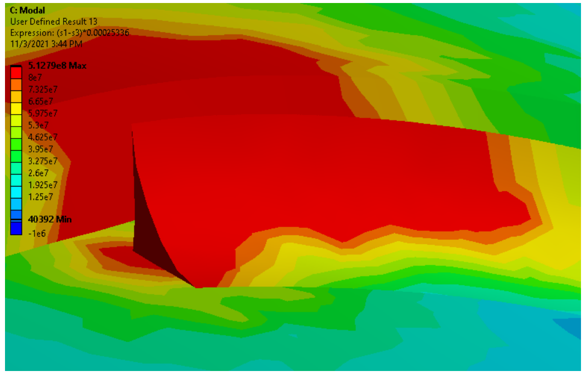
Weld Location 2

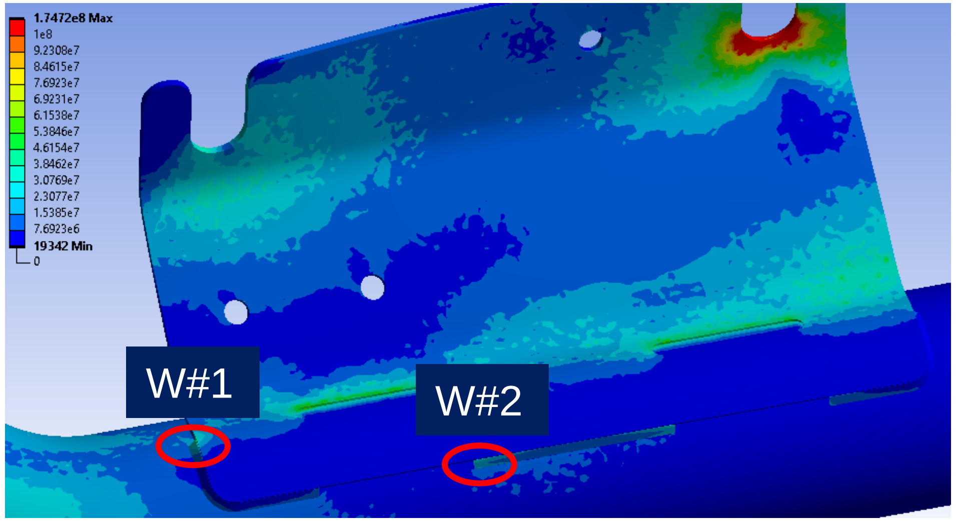




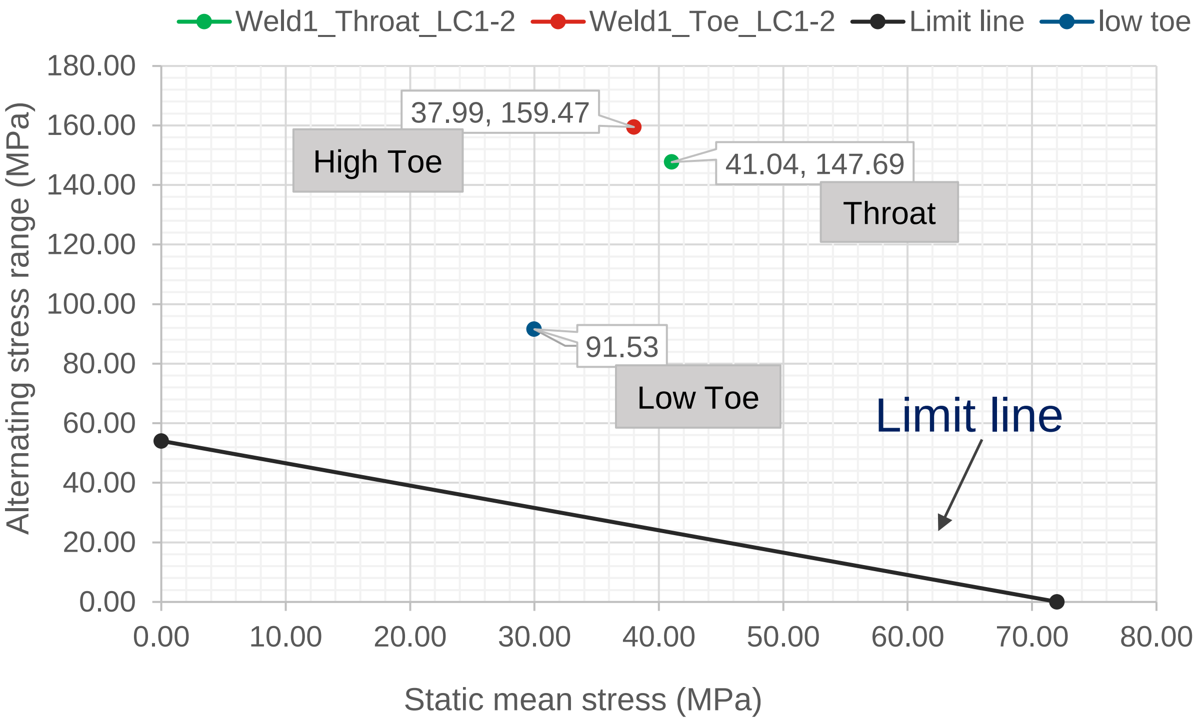
High Stress Concentration

Short tube concave weld:

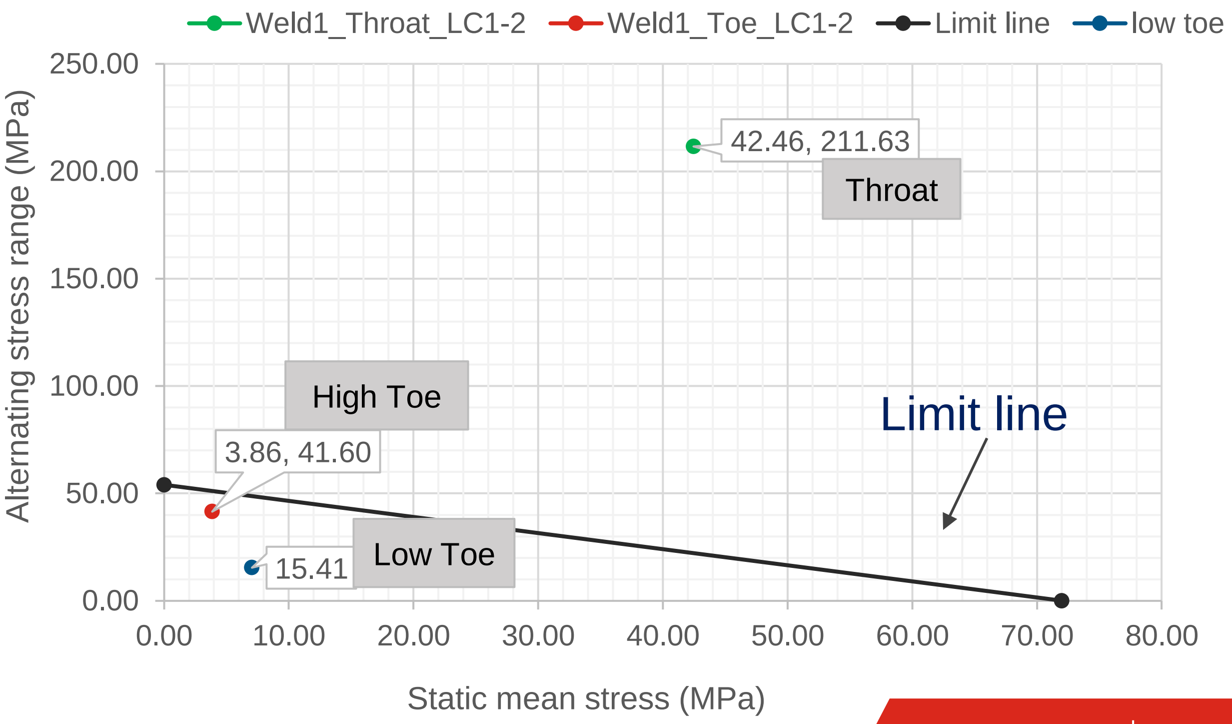




Weld Location 1



Weld Location 2



High Stress Concentration – Results

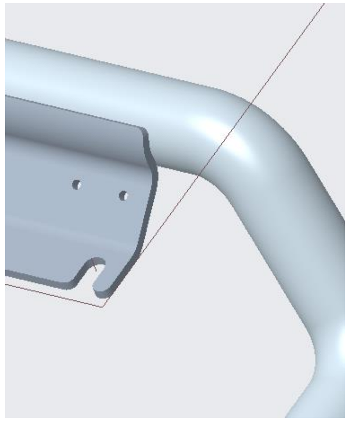
- Weld geometry in new and failed samples is inconsistent
- ANSYS results do not align with theoretical stress concentration geometry
- Best weld concentration per tube and weld location
  - Short tube pipe connection and bracket connection: Flat weld
  - Long tube pipe connection and bracket connection: Concave weld
- These geometries are ideal as they have the lowest stress concentration
  - Ensure weld does not penetrate through the pipe for the short tube, creates concave geometry
  - Meet weld throat size requirement for the long tube, but do not exceed as to create convex geometry with a high-angle weld toe
- Excess stress concentration is a **likely failure mode** for
  - Failed short tubes with a convex or concave weld geometry
  - Failed long tubes with a flat weld geometry

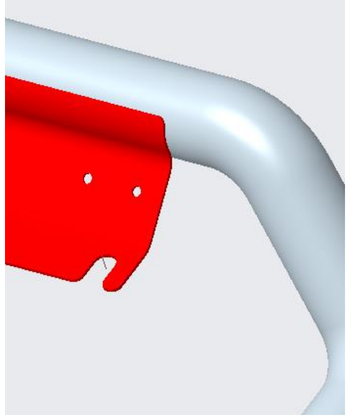
Past Design Changes – Thinner Bracket

- Past design changes of a part or assembly can cause a load redistribution
  - Dynamic loads due to operation
  - Static loads due to assembly
  - Loads from outside sources
- Part changes (slide #) that may have created a redistributed load:
  - **Bracket made thinner** on shorter transfer tube (part #5575183)
- Brackets of both transfer tubes are in the same loading system
  - When the system experiences a uniform displacement, thinner materials have lower resistance to deformation and will withstand less load
  - The thinner bracket absorbs less of the load than previous design
  - Thicker brackets on the long tube may absorb more of the total load
- Conduct an ANSYS simulation to compare stress distribution on the transfer tubes with the old bracket vs the new bracket

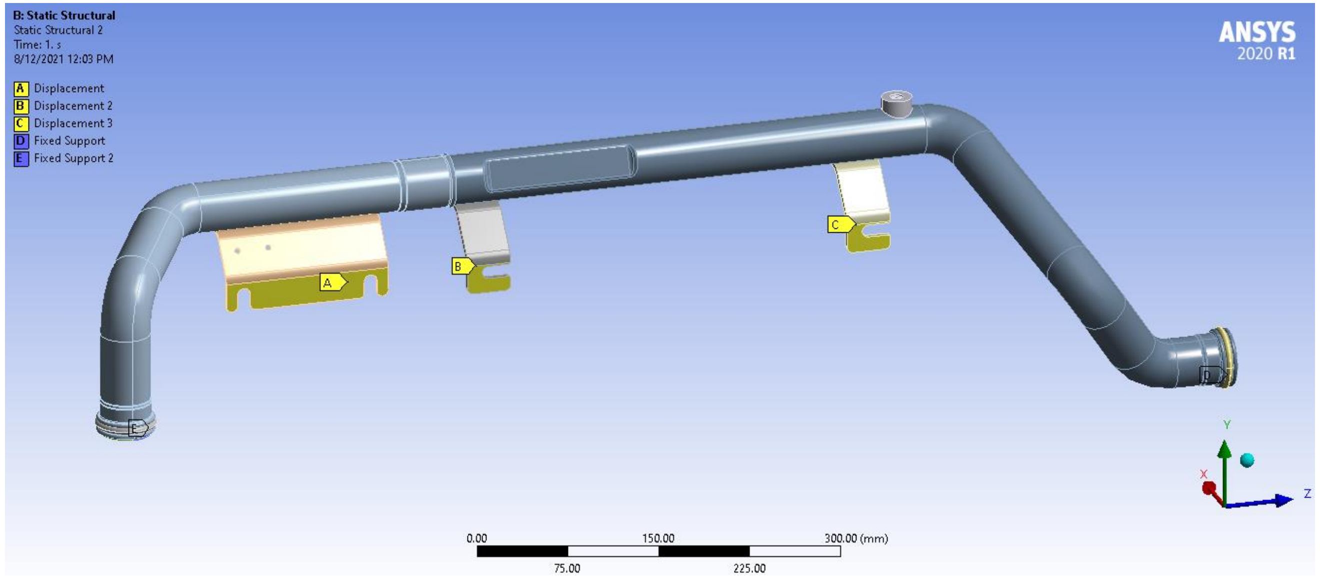
ANSYS Simulation

Old Bracket: 4.8 mm





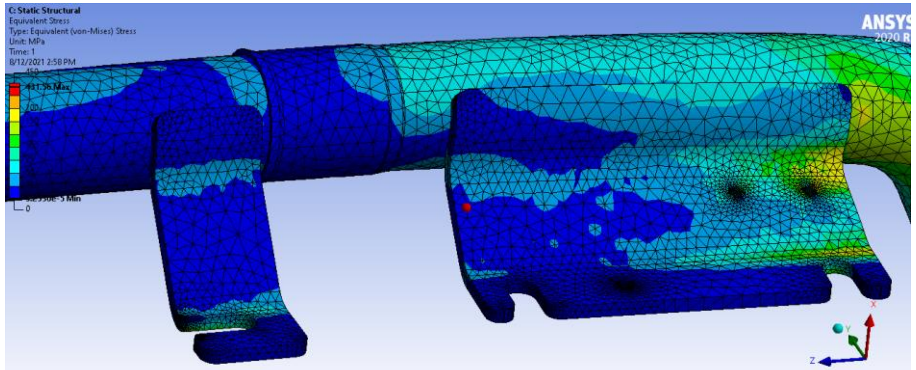
New Bracket: 1.5 mm



- Two ANSYS simulations performed
  - Given displacement perpendicular to each bracket face = 1 mm
  - Same fixed support points at both ends of transfer tubes
  - Both full-system simulations measure equivalent stress
- Each simulation is run with a different bracket thickness, 1.5 and 4.8 mm
- Locations of interest – each welded bracket-to-pipe joint
  - Stress measured at these locations; stress distribution shown
  - Stress distribution compared between simulations

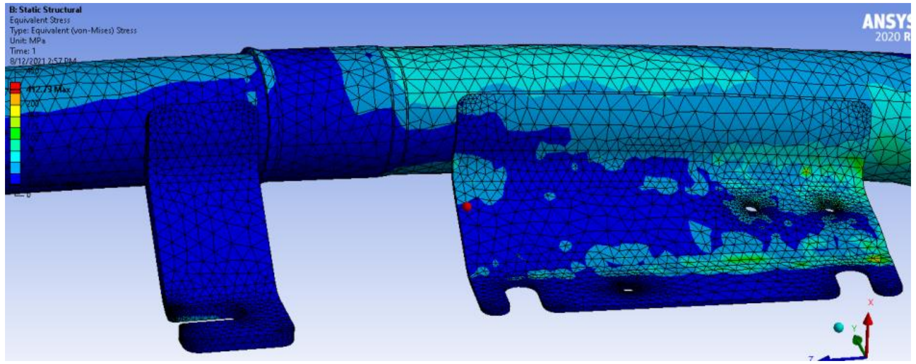
ANSYS Results

With Old Bracket:

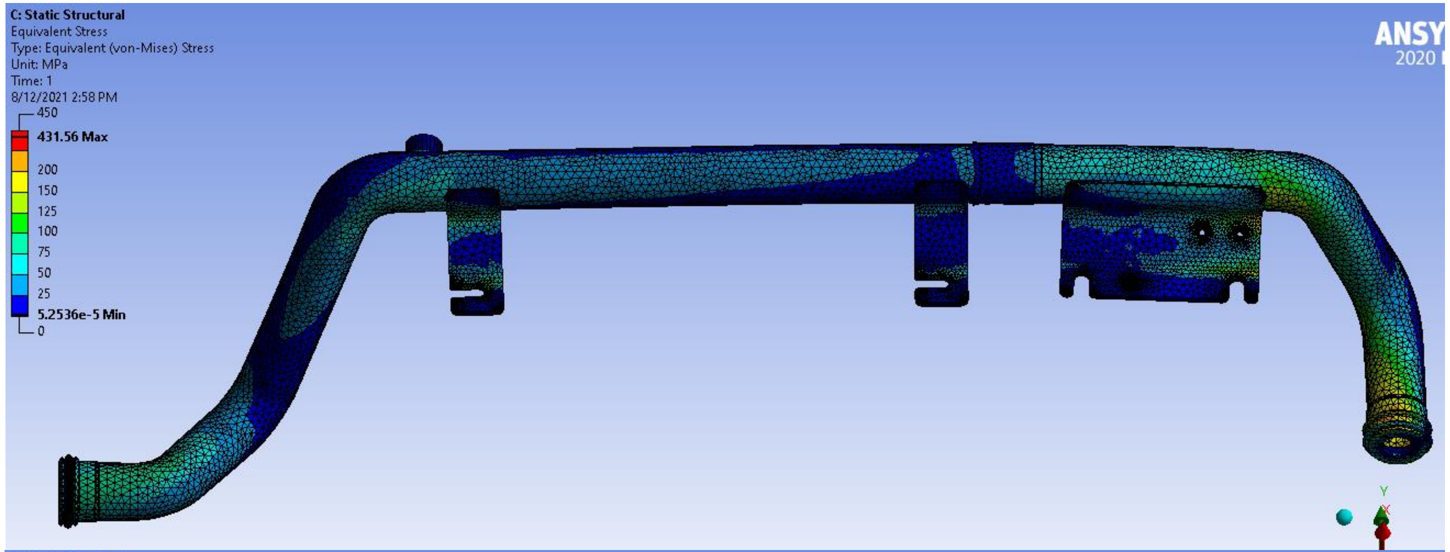


C: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
8/12/2021 2:58 PM

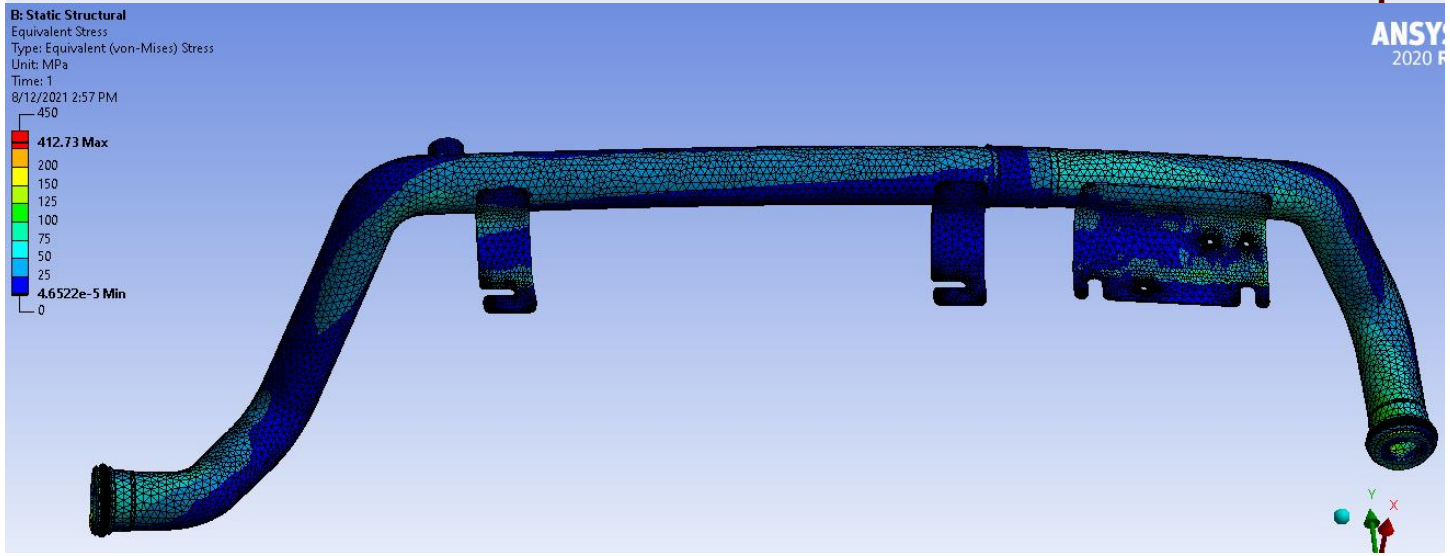
With New Bracket:



B: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
8/12/2021 2:57 PM



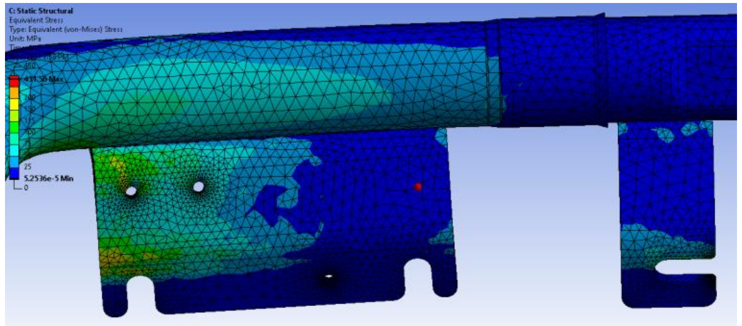
C: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
8/12/2021 2:58 PM

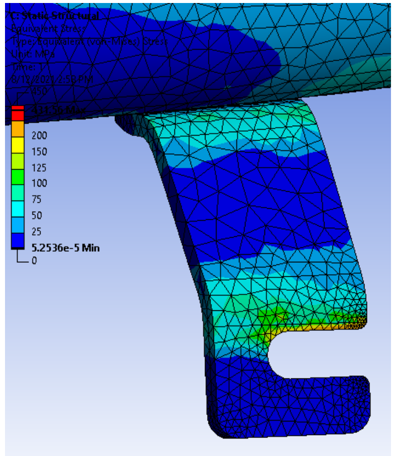


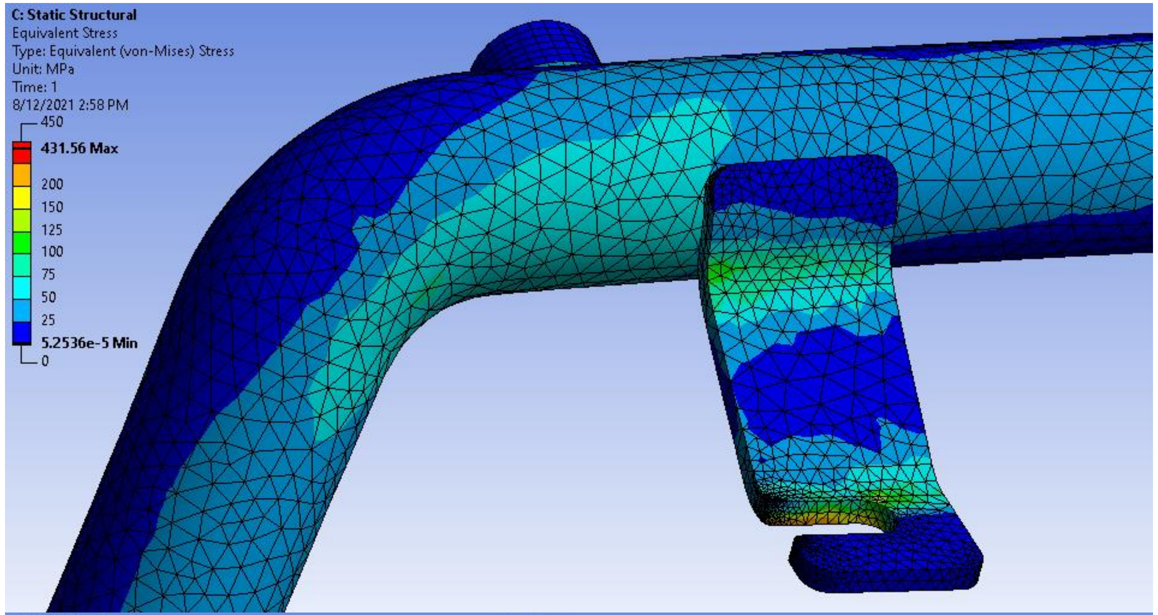
B: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
8/12/2021 2:57 PM

ANSYS Results

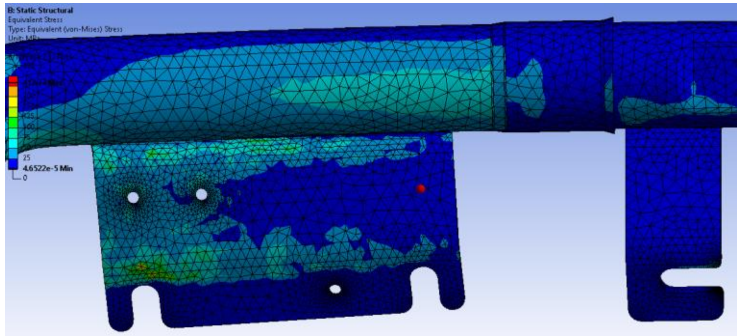
With Old Bracket:

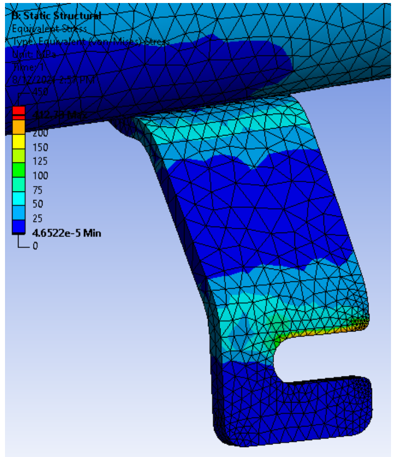

C: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa

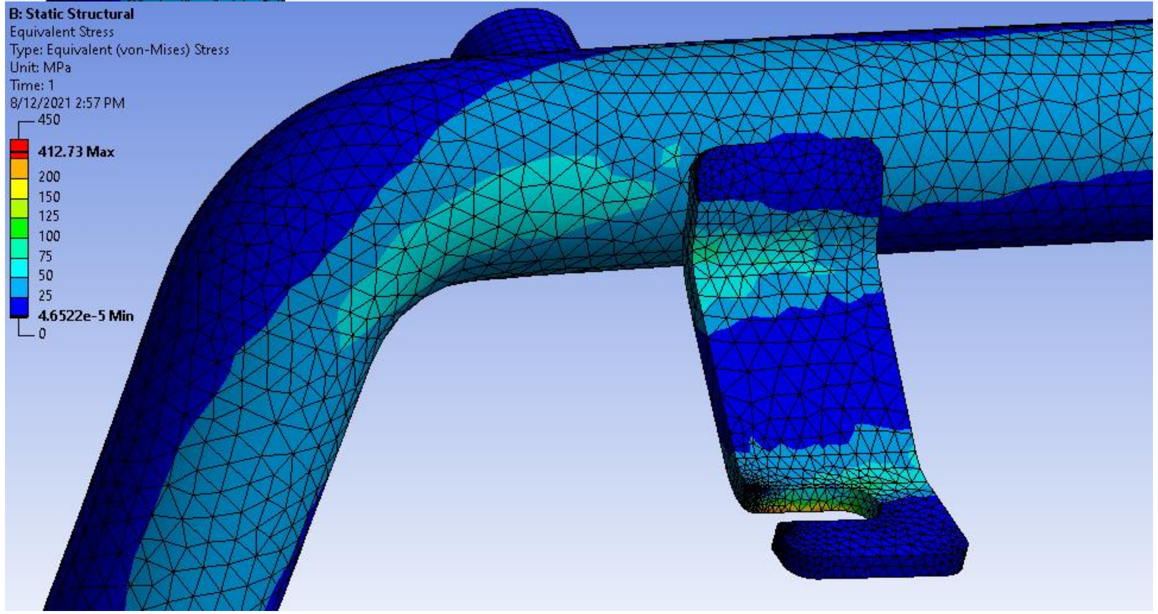



C: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
8/12/2021 2:58 PM

With New Bracket:


B: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa


B: Static Structural
Equivalent Stress


B: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
8/12/2021 2:57 PM

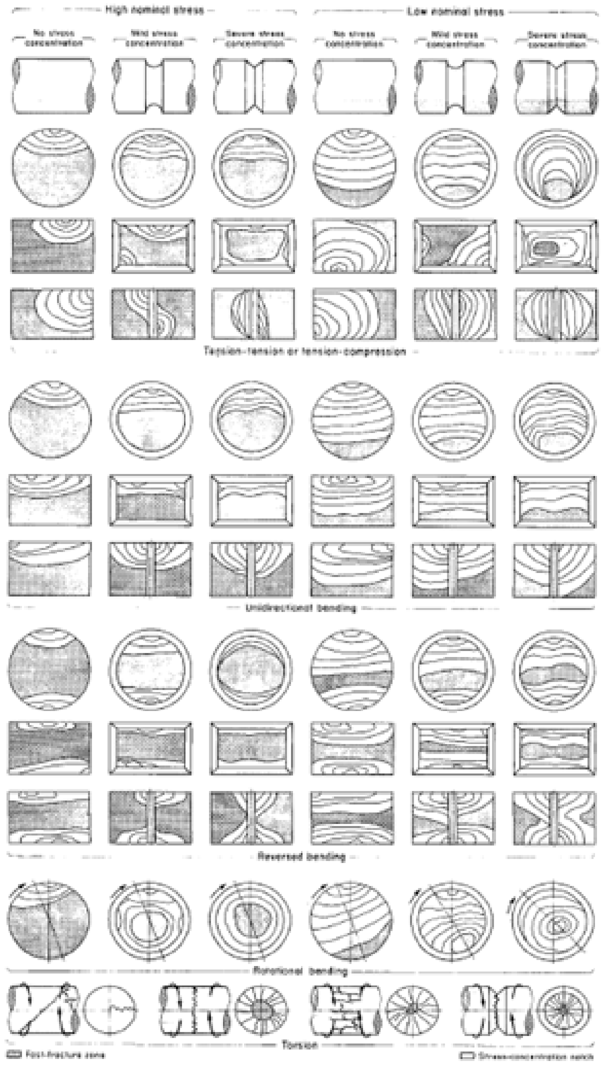
ANSYS Results

- Equivalent stress is lower at each joint with the thinner bracket
- This design change to a thinner bracket:
  - Creates a lower overall load distribution for the same displacement
  - Does not cause more variation in load distribution
  - Does not cause additional stress in any of the welded joints
- This design change is **not** a potential failure mode for any joint
  - Thinner bracket lowers overall loading enough that any shifts in loading distribution do not increase amount of loading at any point
- Loading could be further reduced with thinner long tube brackets (slide #_)
  - The short tube bracket itself is durable despite its 1.5 mm thickness
    - No failures found in the bracket material, only the welded joint
  - Adequate durability also expected for long tube brackets if thickness is reduced

Failure Mode Validation – Material Properties

Material or Surface Defects

Fig. 18 Schematic of marks on surfaces of fatigue fractures produced in smooth and notched components with round, square, and rectangular cross sections and in thick plates under various loading conditions at high and low nominal stress

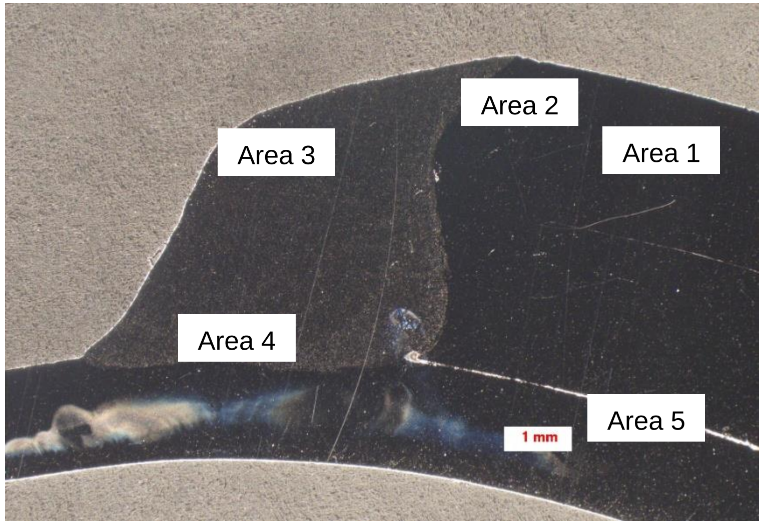


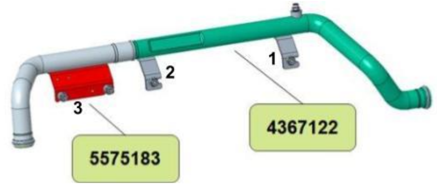
- Check type of fracture

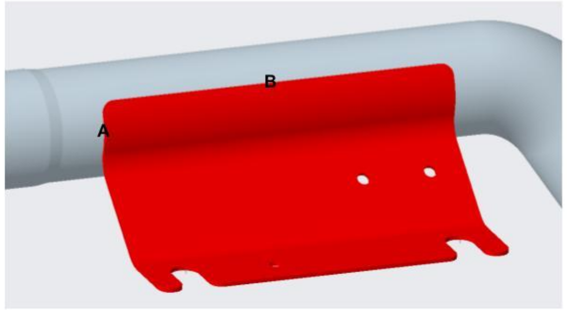
- Observe new and failed samples for evidence of defects
    - Surface inclusions, porosity, discontinuous microstructure
    - Micro cracks, rough surface, witness marks
- Defects may exceed threshold or critical flaw size, leading to single-cycle or fatigue fracture

High Material Hardness

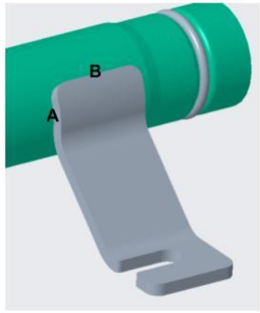
- High hardness leads to low ductility and low fracture toughness
- Excessively low hardness can lead to deformation
- Measured hardness of 3 failed samples at each labeled welded joint:
  - 3 points on the weld
  - 3 points on the base pipe material
  - 3 points on the base pipe material, in the heat-affected zone
  - 2 points on the bracket, both sides (base material)
- Compared hardness results to print specifications
  - Maximum hardness of weldment: 350 HV 500 GF
  - Includes weld, heat-affected zone, and base metal







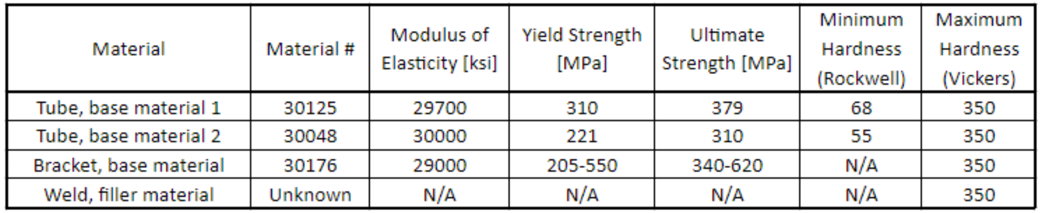
Back of Bracket View (3)



Back of Bracket View (1 and 2)

Hardness Results

Tube	Material	New / Failed	Rockwell B Avg. Hardness
Long tube (4367122)	30125	New	68
		Failed	70.25
Short tube (5575183)	30125 or 30048	New	61.5
		Failed	62.5



Material	Material #	Modulus of Elasticity [ksi]	Yield Strength [MPa]	Ultimate Strength [MPa]	Minimum Hardness (Rockwell)	Maximum Hardness (Vickers)
Tube, base material 1	30125	29700	310	379	68	350
Tube, base material 2	30048	30000	221	310	55	350
Bracket, base material	30176	29000	205-550	340-620	N/A	350
Weld, filler material	Unknown	N/A	N/A	N/A	N/A	350

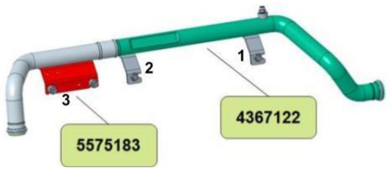
Area	Description	Spec (HV)	Bracket 1						Bracket 2						Bracket 3			
			Long Failed Tube 1		Long Failed Tube 2		New Long Tube		Long Failed Tube 1		Long Failed Tube 2		New Long Tube		Short Failed Tube 1		New Short Tube	
			A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
1	Bracket	N/A	143	166	157	151	162	156	144	151	148	154	149	156	129	134	141	148
2	HAZ Bracket	<350	142	165	170	157	162	148	152	153	168	161	185	140	141	147	153	169
3	Weld	<350	224	190	249	188	236	186	229	191	229	193	242	183	212	216	201	205
4	HAZ Pipe	<350	168	150	154	145	164	144	155	150	127	149	164	142	152	146	140	147
5	Pipe	>85	123	131	122	135	116	118	131	136	120	127	129	119	115	111	121	106
		Rockwell B																
5	Pipe	N/A	67	72	67	74	64	66	72	74	66	70	72	66	64	61	67	56

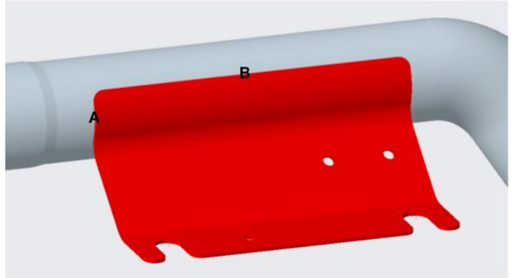
Hardness Results

- No hardness measurements exceed maximum hardness
- No significant difference between new and failed sample hardness values
- Pipe hardness increases at the pipe in the HAZ, expected behavior
- Pipe hardness does not increase at the bracket in the HAZ
    - Potential indication of inadequate weld penetration
- Hardness is highest on the weld, expected
- Long tube average Rockwell hardness meets minimum for material 30125
    - Some long tubes fall slightly below minimum hardness
- Short tube has a lower hardness, material 30048, none below minimum
- Hardness is **not** a primary mode of failure, yet the higher hardness in the HAZ on the pipe makes the material more brittle and therefore susceptible to fracture in the event of deformation due to excess stress

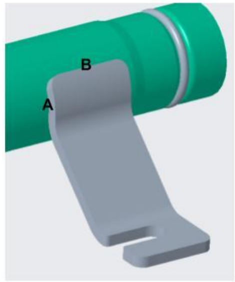
Failure Mode Validation – Improper Weld Properties

Improper Weld Procedure / Geometry





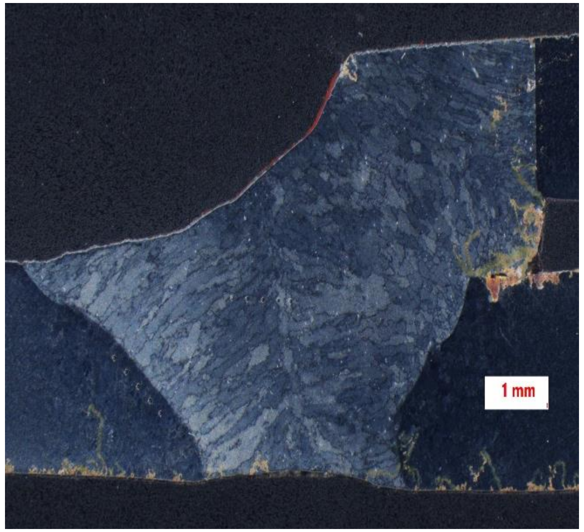
Back of Bracket View (3)



Back of Bracket View (1 and 2)

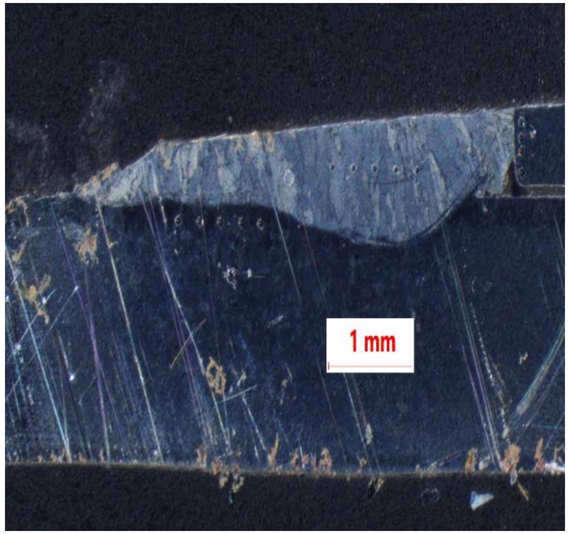
- Inspected weld properties in failed and new samples
  - ISO 5817 standards used to evaluate weld properties
  - Cross-section cut to evaluate each weld
- Evaluated properties: Throat size, porosity, penetration, root fusion
- Multiple imperfections found, **likely modes of failure**
  - Most welds on bracket 1 and 2 do not meet the minimum throat size, 3 mm
  - Root gaps of several welds exceed max limit of 0.6 mm for a 3 mm throat size
    - The larger the root gap, the smaller the area of fusion and the weaker the joint
  - Most welds exceed allowable porosity, 1.5%
  - Some welds have minimal weld penetration, only one critically inadequate weld
  - Clearance between bracket and pipe near weld that can weaken the joint
- Supplier quality issue; contacted suppliers to make changes in weld process

Weld Cross-Section Etches – Bracket 1, Location A



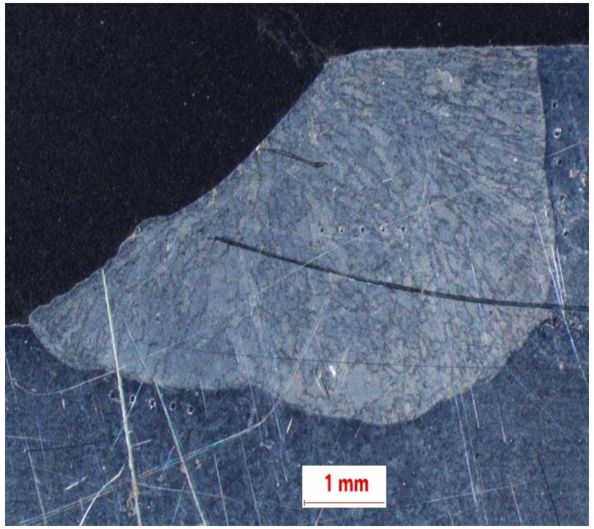
Failed Tube #1

- Throat size = 1.769 mm
- Excess weld penetration
- Weld root concavity
- Porosity > 1.5%
- Bracket-tube clearance



Failed Tube #2

- Lack of fusion, bracket side
- No throat size due to this
- Porosity > 1.5%
- One large gas pore, 0.135 mm



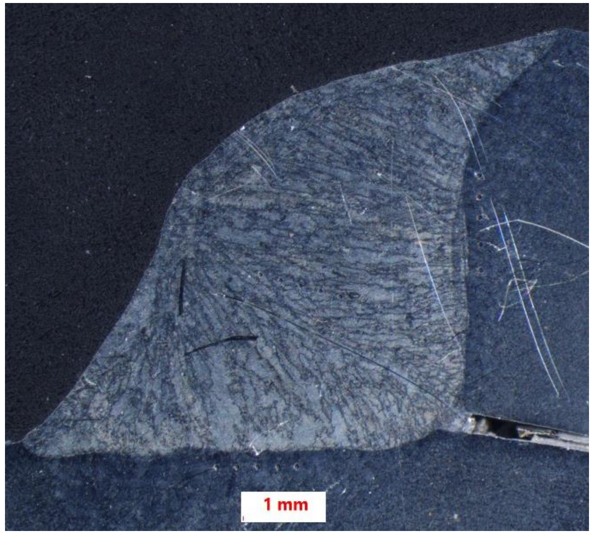
New Tube

- Throat size = 2.355 mm
- Porosity > 1.5%

Weld Cross-Section Etches – Bracket 1, Location B

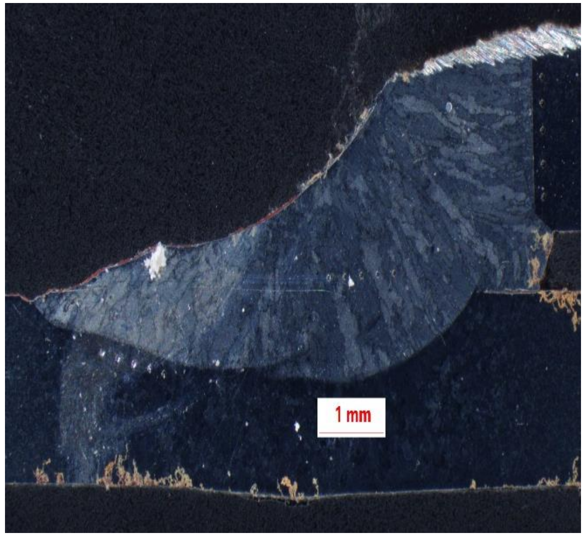
Failed Tube #1
- Throat size = 3.19 mm
- Porosity > 1.5%
- Bracket-tube clearance

Failed Tube #2
- Throat size = 2.678 mm
- Porosity > 1.5%
- Gas pores, HAZ tube side
- Size range = 0.05 - 0.138 mm



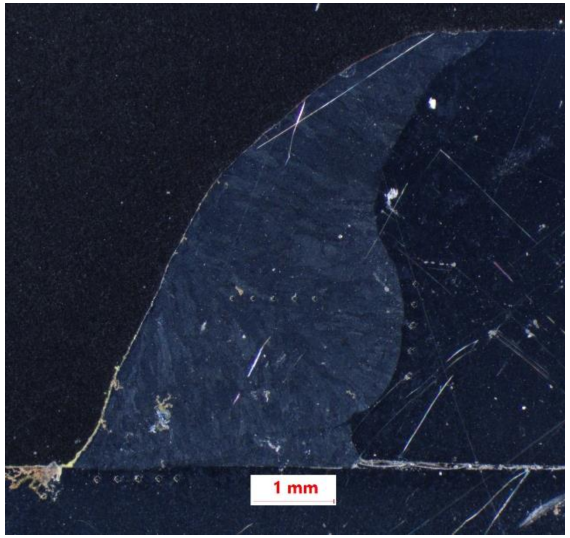
New Tube
- Throat size = 4.176 mm
- Porosity > 1.5%

Weld Cross-Section Etches – Bracket 2, Location A



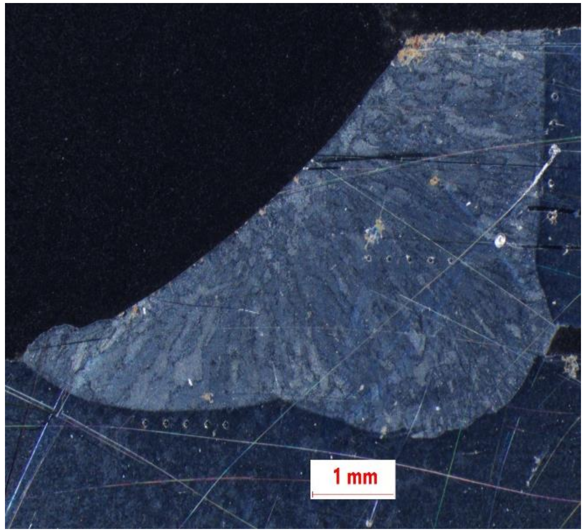
Failed Tube #1

- Throat size = 1.985 mm
- Porosity > 1.5%
- Small gas pores
- Largest gas pore = 0.122 mm
- Undercut on the left toe



Failed Tube #2

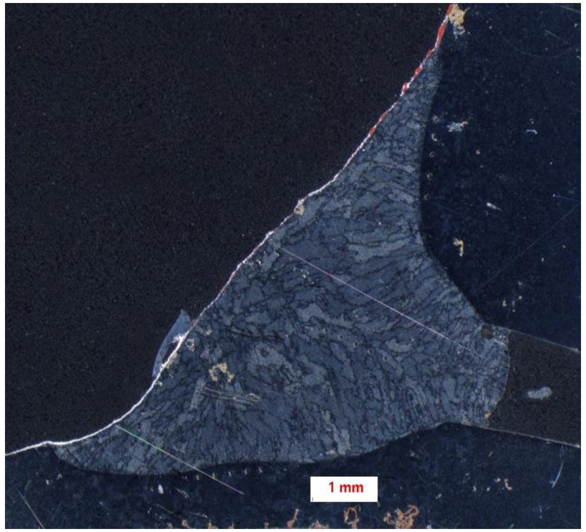
- Throat size = 3.131 mm
- Porosity > 1.5%
- Small gas pores



New Tube

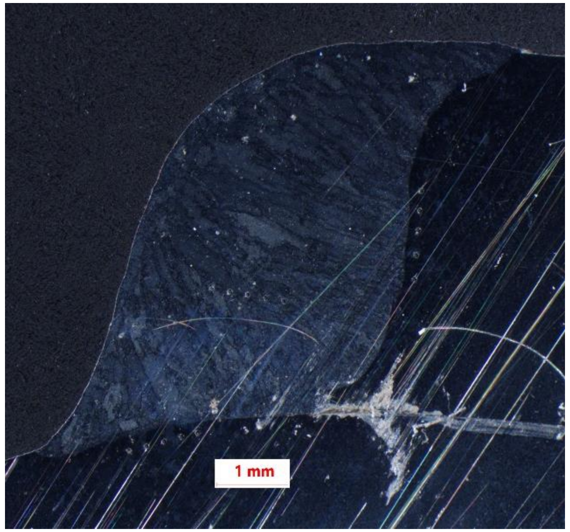
- Throat size = 2.803 mm
- Porosity > 1.5%
- Single gas pore, 0.184 mm

Weld Cross-Section Etches – Bracket 2, Location B



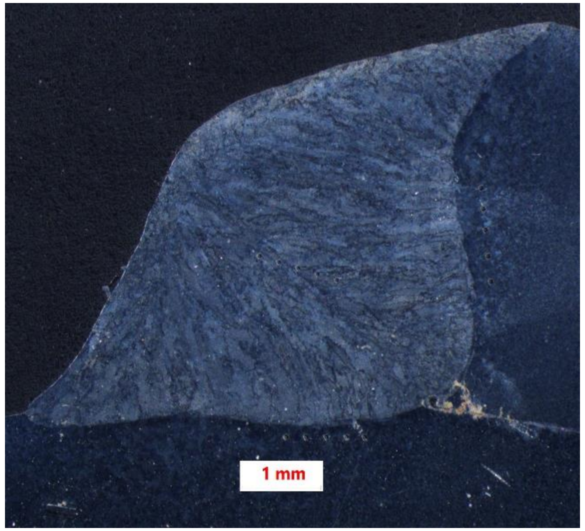
Failed Tube #1

- Throat size = 2.575 mm
- Porosity > 1.5%
- Lack of root fusion
- Small gas pores
- Largest gas pore = 0.218 mm
- Bracket-tube clearance



Failed Tube #2

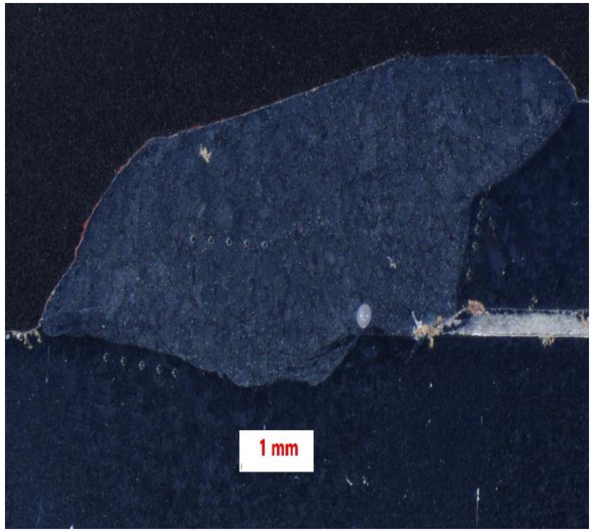
- Throat size = 2.629 mm
- Porosity > 1.5%
- Small gas pores
- Bracket-tube clearance



New Tube

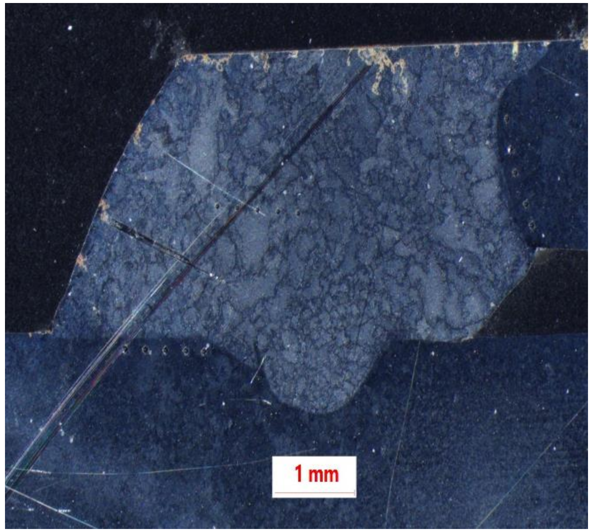
- Throat size = 4.184 mm
- Little weld porosity

Weld Cross-Section Etches – Bracket 3



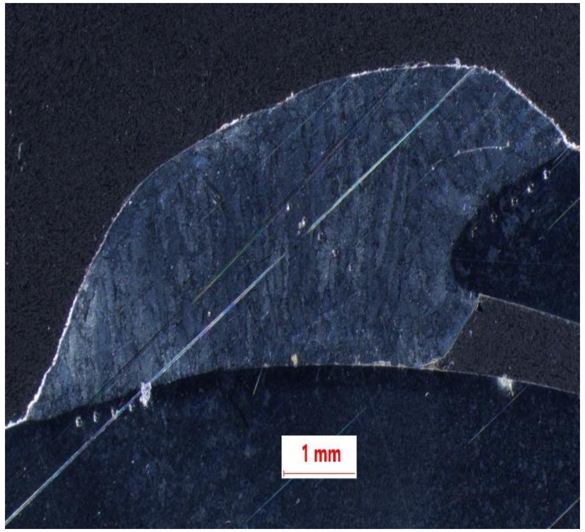
Failed Tube, Location A

- Throat size = 2.251 mm
- Porosity > 1.5%
- One gas pore, 1.248 mm
- Slight undercut on left toe



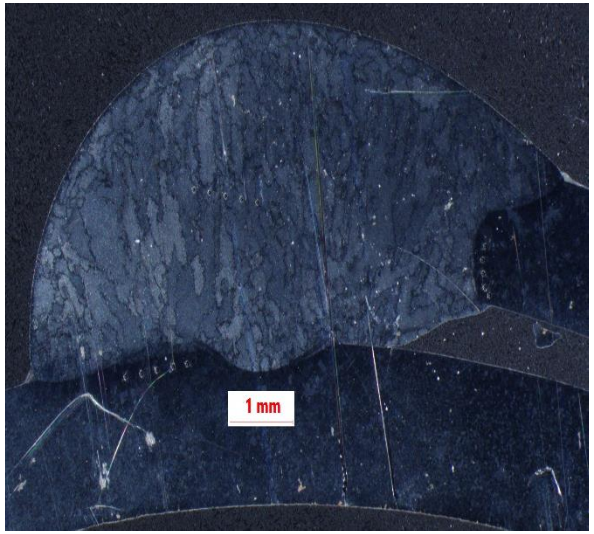
New Tube, Location A

- Throat size = 1.813 mm
- Little porosity
- Small gas pores
- Bracket-tube clearance



Failed Tube, Location B

- Throat size = 1.914 mm
- Porosity > 1.5%
- Bracket-tube clearance



New Tube, Location B

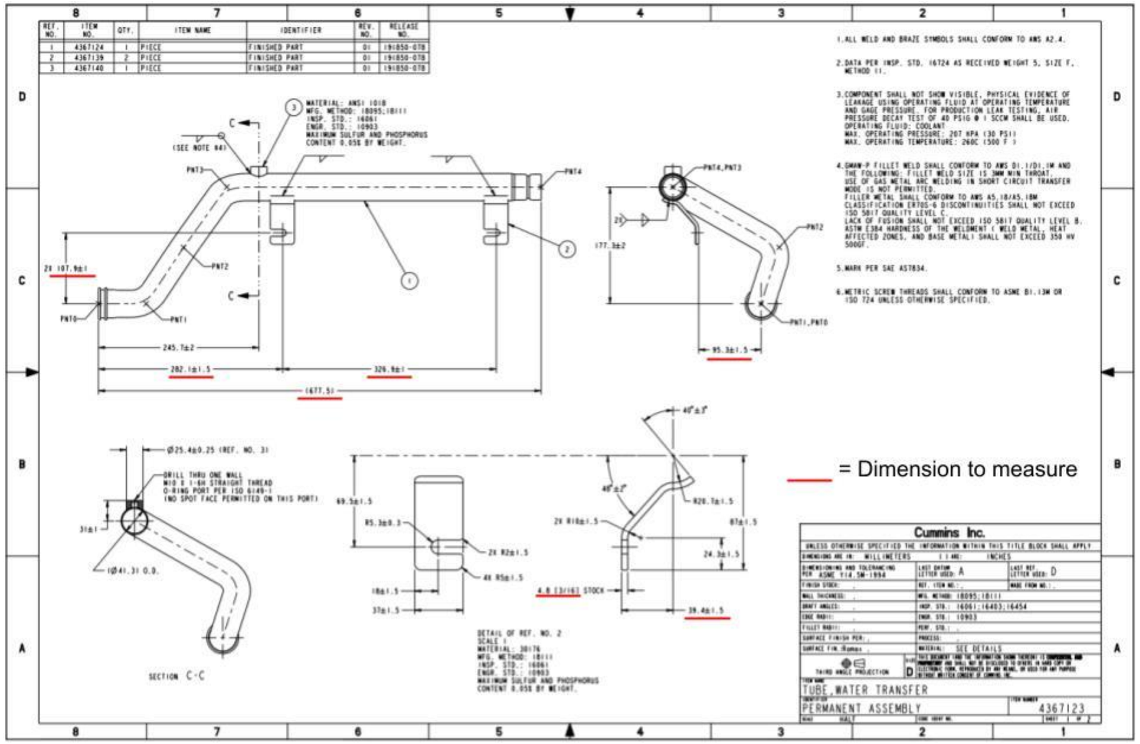
- Throat size = 2.101 mm
- Little porosity
- Small gas pores
- Bracket-tube clearance

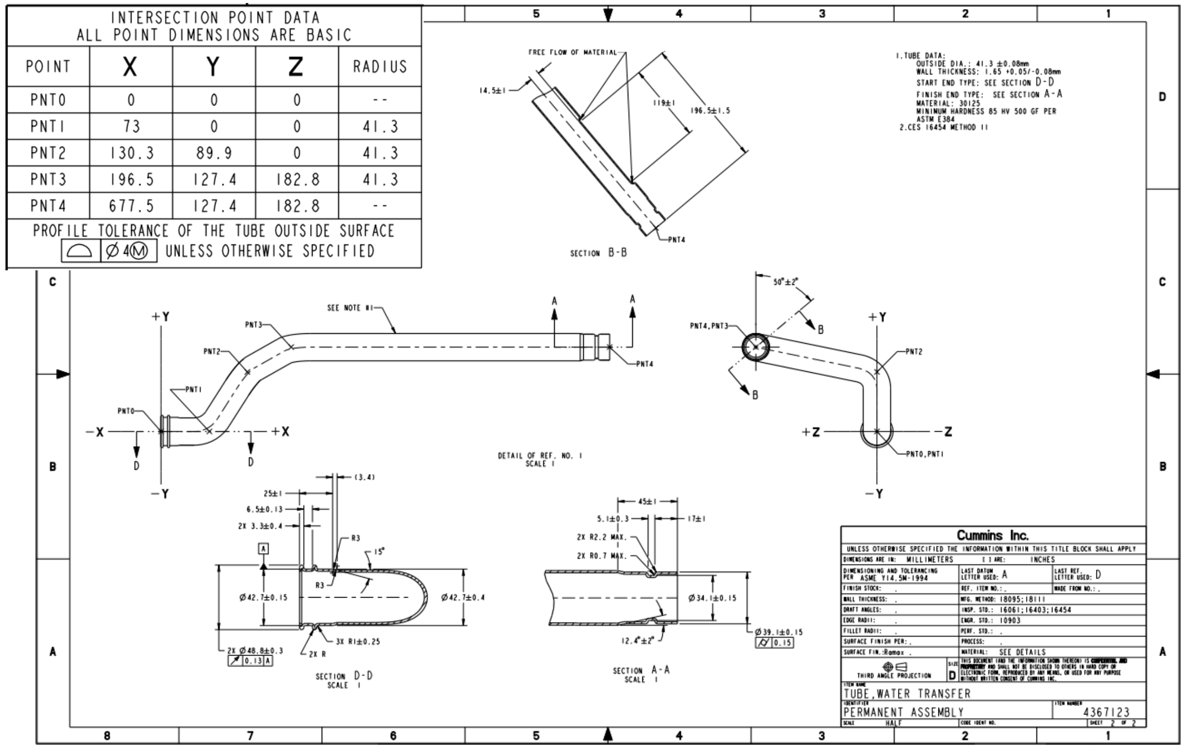
Observations and Conclusion

- Prints give incomplete weld specifications and material properties
  - May have led to the supplier quality issues – inconsistent welding in production
- Each failure impacts either the strength of the joint or the fit of the bracket

Failure Mode Validation – Dimensional Quality

Dimensional Quality – Transfer Tube (Part #4367122)





INTERSECTION POINT DATA
ALL POINT DIMENSIONS ARE BASIC

POINT	X	Y	Z	RADIUS
PNT0	0	0	0	--
PNT1	73	0	0	41.3
PNT2	130.3	89.9	0	41.3
PNT3	196.5	127.4	182.8	41.3
PNT4	677.5	127.4	182.8	--

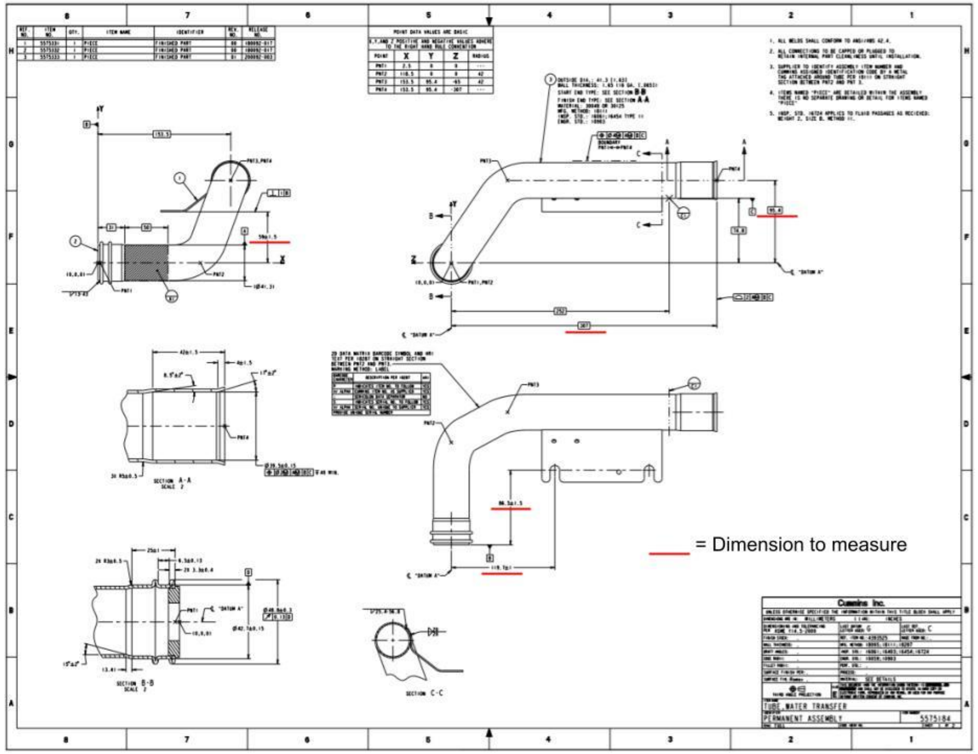
PROFILE TOLERANCE OF THE TUBE OUTSIDE SURFACE
⌓ | Ø 4Ⓜ UNLESS OTHERWISE SPECIFIED

- Key dimensions for placement of the transfer tube and intersection points
- Dimensions out of tolerance range can cause imperfect fit / internal stress
- 5 new sets of transfer tubes measured and compared to print dimensions

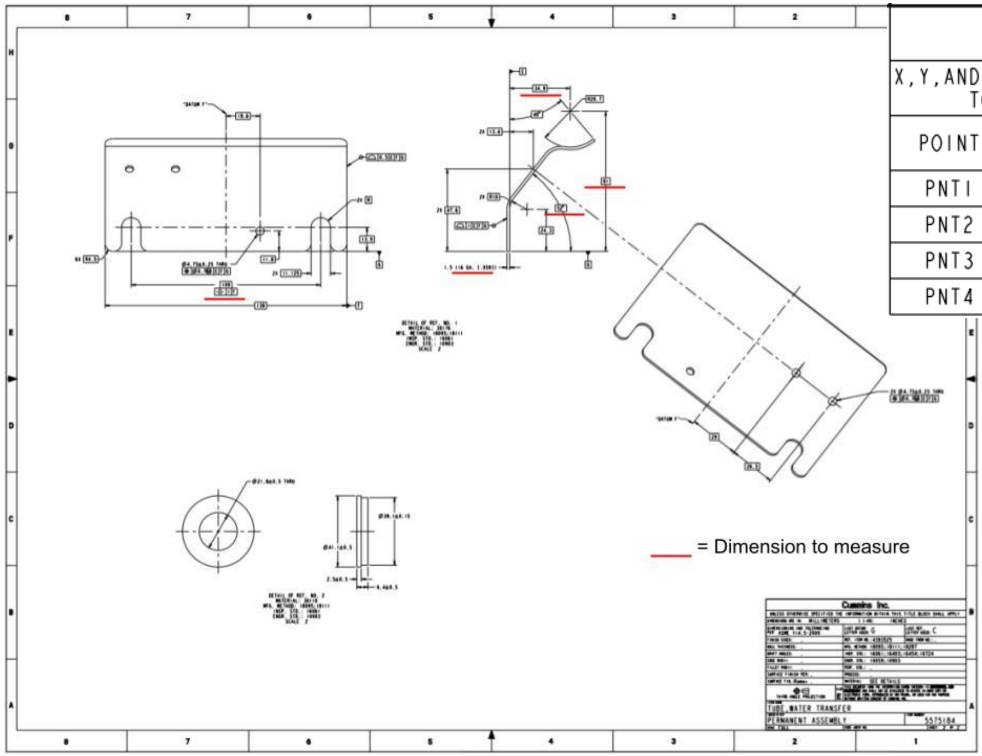
4367122 Measurement Results

- Consistently failed measurements
  - Intersection point 2 position, all directions, and point 4 position, x direction
  - No bracket positioning failed
- No dimensional variation greater than 0.5 mm between samples
- Failure due to excess static stress from:
  - Dimensional deviation at point 2 is **not** a failure mode
    - Point 2 position is not relevant to how the tubes fit to block
  - Deviation at point 4 x-direction is a **low-likelihood** failure mode
    - Point 4 position has a minor effect on how the tubes fit to block
  - Dimensional variation between parts is **not** a failure mode

Dimensional Quality – Transfer Tube (Part #5575183)



= Dimension to measure



= Dimension to measure

POINT DATA VALUES ARE BASIC

X,Y,AND Z POSITIVE AND NEGATIVE VALUES ADHERE TO THE RIGHT HAND RULE CONVENTION

POINT	X	Y	Z	RADIUS
PNT1	2.5	0	0	---
PNT2	118.5	0	0	42
PNT3	153.5	95.4	-65	42
PNT4	153.5	95.4	-307	---

- Key dimensions of the placement of the tube and bracket dimensions
- Dimensions out of tolerance range can cause imperfect fit / internal stress
- 5 new sets of transfer tubes measured and compared to print dimensions

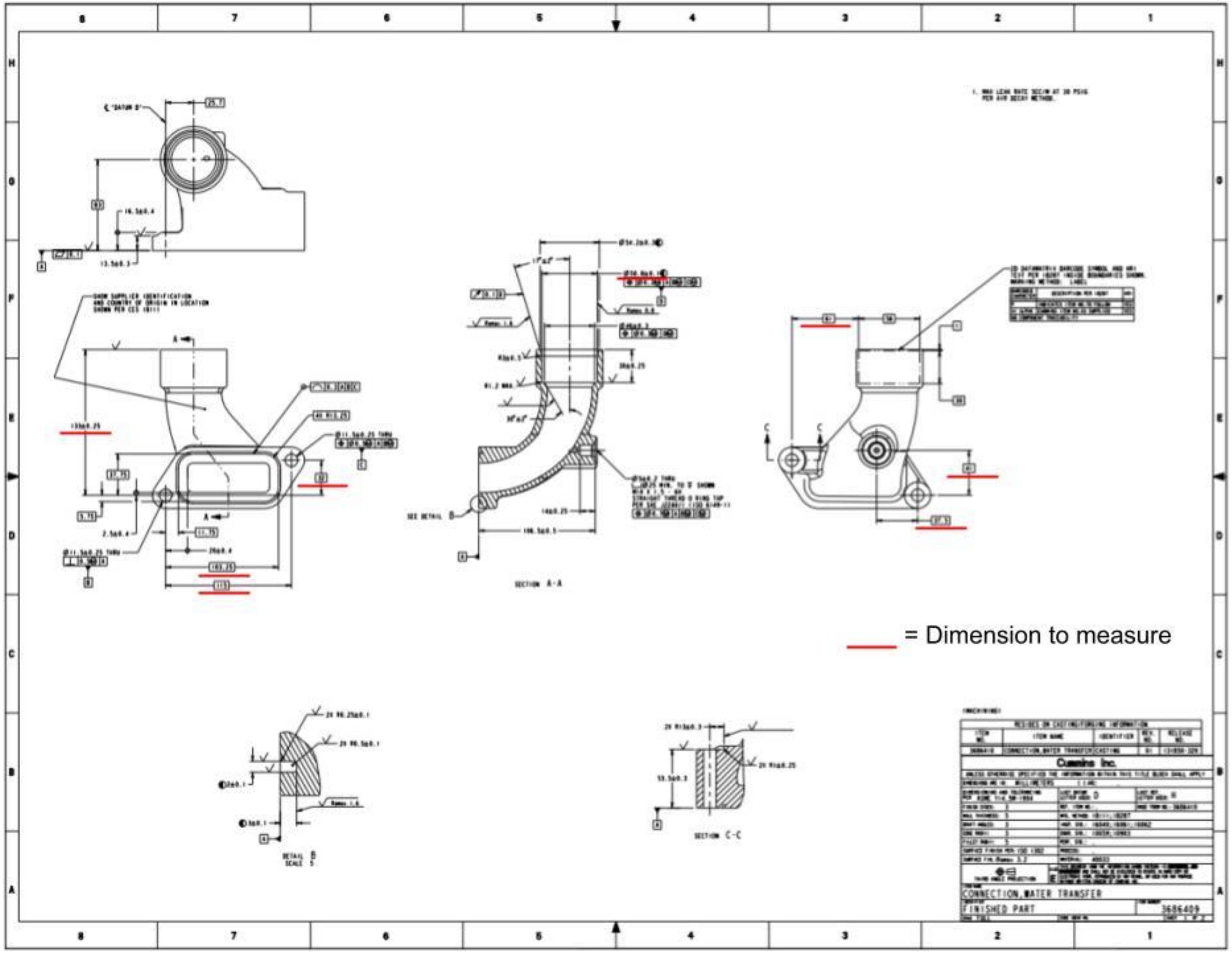
5575183 Measurement Results

- Failed measurements
  - All samples failed for either x or z component of point 4 position
  - Sample 3 failed at the bracket angle
    - Did not fail for any bracket positioning dimension
  - 2 samples failed at bracket length and width dimensions
    - However, all samples passed for bracket face to point 1 positioning
  - Same 2 samples also failed at y-direction bracket slot location
- Effect of failed measurements
  - Point 4 position has a minor impact on how the tube fits the block
  - Bracket positioning has a more significant impact on fit
  - Bracket dimensions are not relevant if slot position is accurate

5575183 Measurement Results

- More dimensional variation than long tube, but none greater than 3 mm
- Failed dimensions are not consistent; different deviations
- Failure due to excess static stress from:
  - Deviation at point 4 any direction is a **low-likelihood** failure mode
    - Point 4 position has a minor effect on how the tubes fit to block
  - Incorrect bracket dimensions is a **low-likelihood** failure mode
    - If these dimensions do not cause incorrect positioning
  - Incorrect bracket position in any direction **is** a likely failure mode
  - Dimensional variation of parts is a **low-likelihood** failure mode

Key Dimensions – Connector (Part #3686409)



- Dimensional issues commonly found in these connector parts
- 4 samples chosen with visually-evident machining and dimensional errors
- Dimensions shown measured for each sample
    - Evaluated conformance to print tolerances
    - Determined significance of dimensional variation

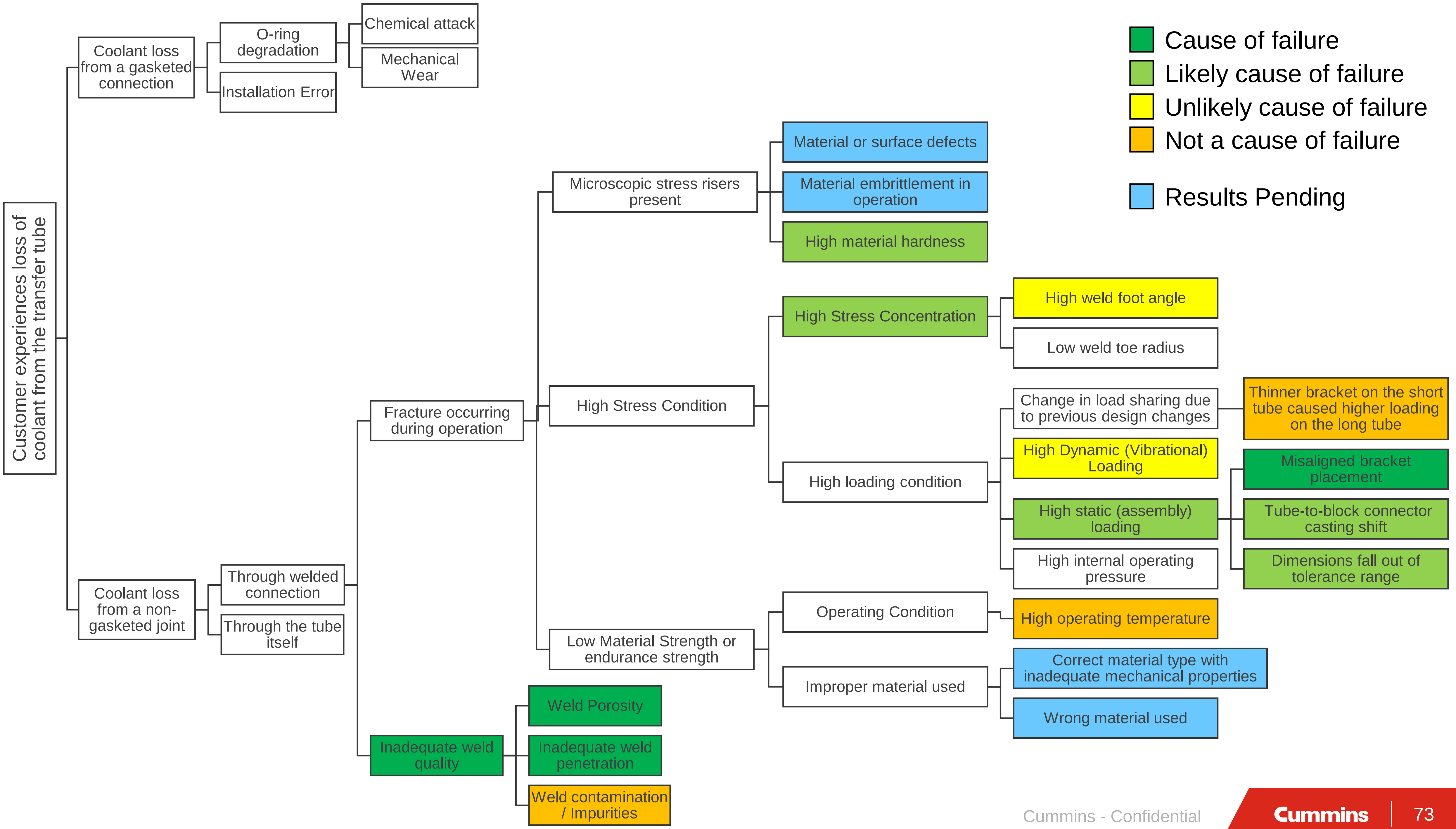
3686409 Measurement Results

- All bolt hole diameters are within tolerance range
- Deviation of bolt hole position measurements without tolerances
  - Datum B position does not significantly deviate
  - Datum C position deviates in the x direction, largest deviation is -0.2603 mm
  - Distance from datum B to end of tube fit significantly varies in 2 of 4 samples
  - x and z distance from datum B to center hole vary significantly for one sample
    - x direction variation is -0.44 mm in sample 2
    - z direction variation is -0.64 mm in sample 4
  - Datum D position deviates consistently in all directions and samples
- Dimensions with tolerances that consistently fall outside tolerance range:
  - Distance from datum B to top of connector consistently fails at different values
- Datum C perpendicularity to surface fails in sample #4

3686409 Measurement Results

- Measurement failures that have an impact on pipe fit and internal stress
  - Datum C position deviates in the x direction
  - Distance from datum B to end of tube fit significantly varies
  - Distance from datum B to end of tube fit variation (Nominal = 103.25 mm)
    - These three dimensions have an impact on the x-direction fit of the connector
    - Any connector fit deviation translates to the fit of the pipe within the connector
  - Datum D position variation
    - This position affects the horizontal x-y location that the pipe fits to the connector
  - Distance from datum B to top of connector
    - If this dimension is too long, it may push pipe upward (z-direction)
- These dimensional errors found in the 3686409 connector **are** a likely cause of failure due to internal stress caused by imperfect fit

Determined Failure Modes and Recommendation



🟩 Cause of failure
🟢 Likely cause of failure
🟨 Unlikely cause of failure
🟧 Not a cause of failure

🟦 Results Pending

- Customer experiences loss of coolant from the transfer tube
  - Coolant loss from a gasketed connection
    - O-ring degradation
      - Chemical attack
      - Mechanical Wear
    - Installation Error
  - Coolant loss from a non-gasketed joint
    - Through welded connection
    - Through the tube itself
      - Fracture occurring during operation
        - Microscopic stress risers present
          - 🟦 Material or surface defects
          - 🟦 Material embrittlement in operation
          - 🟢 High material hardness
        - High Stress Condition
          - 🟢 High Stress Concentration
            - 🟨 High weld foot angle
            - Low weld toe radius
          - High loading condition
            - Change in load sharing due to previous design changes
              - 🟧 Thinner bracket on the short tube caused higher loading on the long tube
            - 🟨 High Dynamic (Vibrational) Loading
            - 🟢 High static (assembly) loading
              - 🟩 Misaligned bracket placement
              - 🟢 Tube-to-block connector casting shift
              - 🟢 Dimensions fall out of tolerance range
            - High internal operating pressure
        - Low Material Strength or endurance strength
          - Operating Condition
            - 🟧 High operating temperature
          - Improper material used
            - 🟦 Correct material type with inadequate mechanical properties
            - 🟦 Wrong material used
      - 🟩 Inadequate weld quality
        - 🟩 Weld Porosity
        - 🟩 Inadequate weld penetration
        - 🟧 Weld contamination / Impurities

Determined Failure Modes

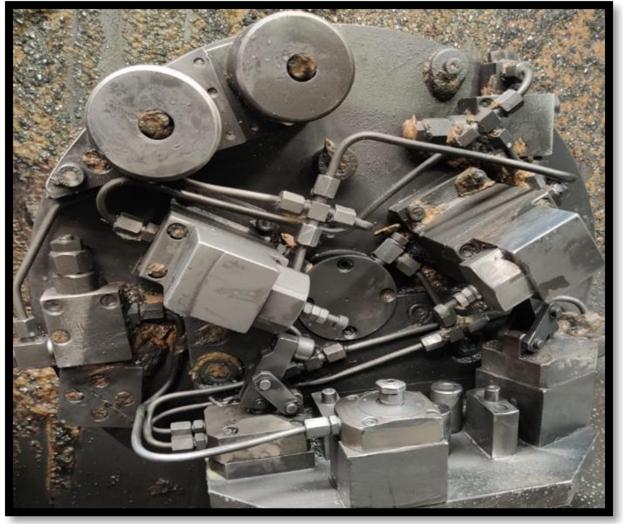
- High stress concentration – weld toe locations and weld edges
  - Failed short tubes with a convex or concave weld geometry
  - Failed long tubes with a flat weld geometry
- Material and surface defects
- Dimensional quality issues – inadequate fit and static assembly stress
  - Bracket position dimensions out of tolerance on 5575184
  - Multiple connector dimensions varied and out of tolerance range
  - Test cell strain gauge operation shows that the fit of a properly-dimensioned part is unlikely to be an issue

Determined Failure Modes

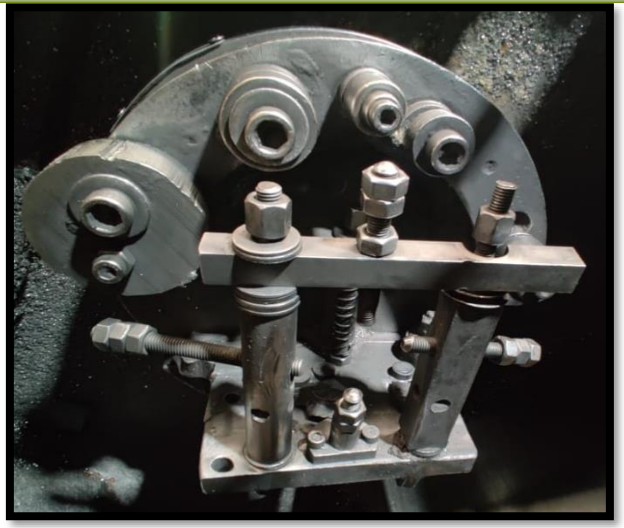
- Weld supplier quality issues – weakened weld joint
  - Excess weld porosity, > 1.5% common
  - Weld throat size does not meet the 3 mm minimum on some 4367122 parts
  - Root gaps exceed allowable 0.6 mm length
  - A few cases of inadequate weld penetration
- Hardness in pipe heat-affected zone greater than base material hardness
  - Expected behavior, but this is a factor that may cause failure at the joint before the pipe if the failure mode is some form of excess stress
  - Supplier test confirmed that joint location fails with less vibrational loading

SQIE Solution – Connector Dimensional Quality

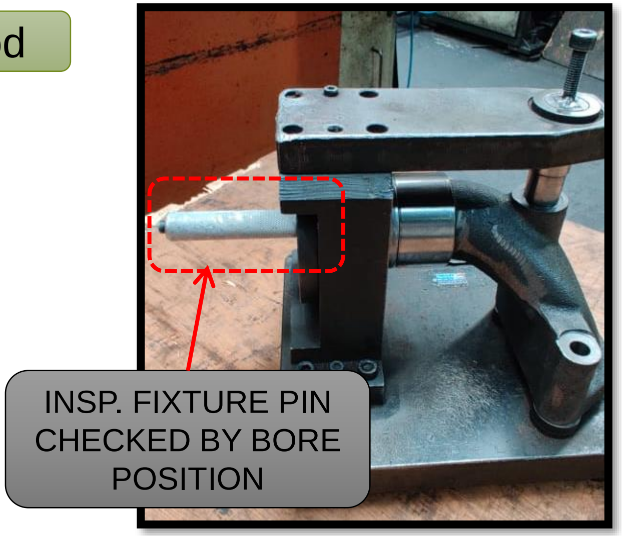
- Connector supplier: [redacted]
- 3 hydraulic and 1 manual clamping mechanism in each CNC machine
- Manual clamping mechanism identified as cause of dimensional issues
- Replaced manual clamping mechanism with hydraulic clamping mechanism
- Should significantly reduce error in positioning from manual mechanism



Hydraulic Clamping Production Method



Manual Clamping Production Method



INSP. FIXTURE PIN CHECKED BY BORE POSITION

SQIE Solution – 5575184 Weld Quality

As-run

After changes

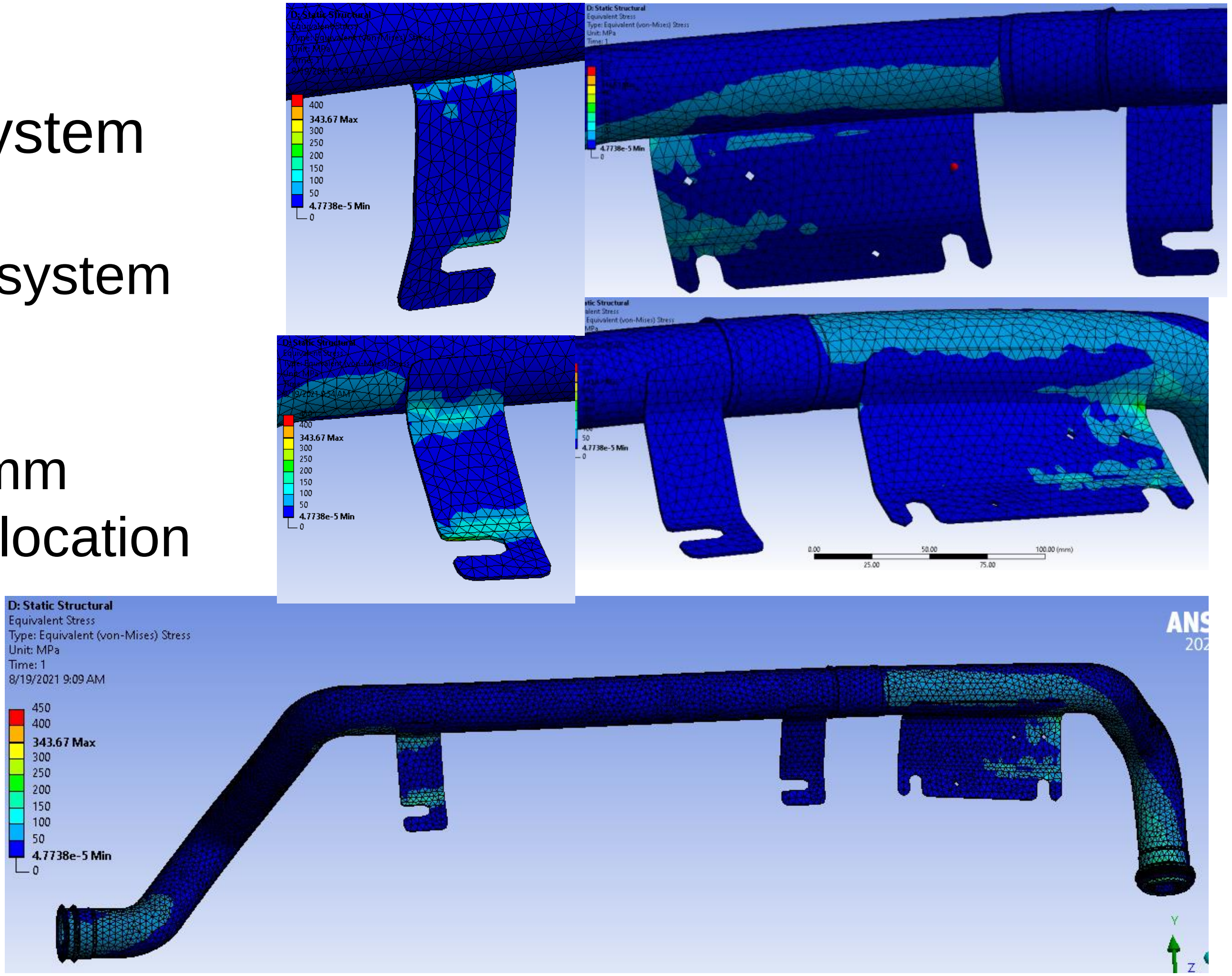
- 5575184 supplier: [redacted]
- Weld heat increased to ensure adequate weld penetration
    - Still within specified WPS parameters
    - Hardness testing to confirm no significant change
    - Did a “runout” to ensure no burnthrough or undercut
- Torch position and work angles changed in welding robot program to eliminate ropey appearance – perpendicular weld application
- Dye penetrant testing conducted to ensure no undercut or cracking issues
- Evaluated fixturing between bracket and pipe to ensure correct placement
- Reviews conducted for use of anti-spatter and cleaning operations
- Communicated changes and expectations with welders/operators, quality control, engineering, and production management

Design Solution – High Static / Dynamic Stress

- Excess static / dynamic stress unlikely, but more testing may be necessary
  - Some high-stress spots may have not been registered in strain gauge test
  - We could not measure on the weld itself
- Certain conditions yielded higher strain, but did not exceed allowable limits
- Implement a cost-justifiable solution to reduce overall loading on the system
- <u>Solution</u>: **Change long tube bracket thickness to 1.5 mm**
  - Short tube brackets have already been reduced to this thickness
  - Thinner brackets reduce stress due to deflection
  - Can offset any remaining quality issues from incomplete SQIE solutions
    - Weld quality issues that lower allowable stress on the joint to below existing stress
    - Dimensional quality issues that increase assembly stress on the joint
- ANSYS analysis completed to measure stress reduction from original design

Design Solution – High Static / Dynamic Stress

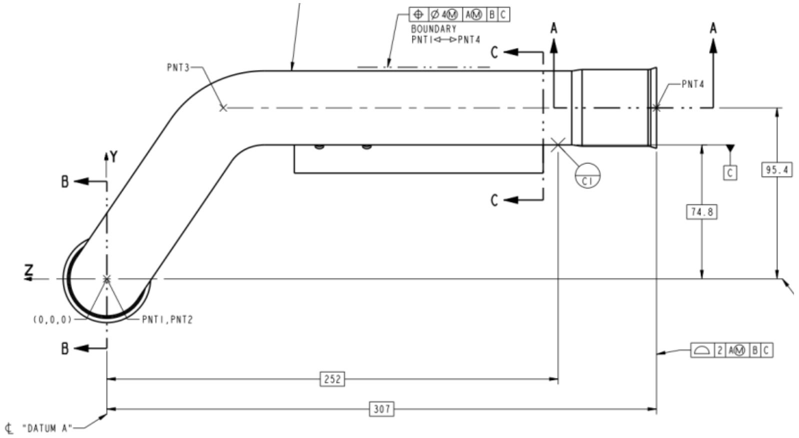
- ANSYS static stress analysis on system with 1.5 mm 4367122 brackets
  - Compared to results from current system with 4.8 mm 4367122 brackets
    - (Slide #_)
  - Stress distribution is lower in 1.5 mm 4367122 bracket system at every location
- Cost justification needed
  - Tooling cost will be present
  - Piece part cost reduction likely



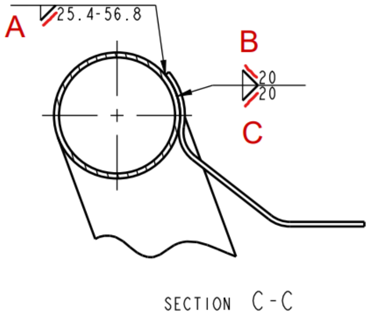
D: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
8/19/2021 9:09 AM

Design Solution – High Stress Concentration

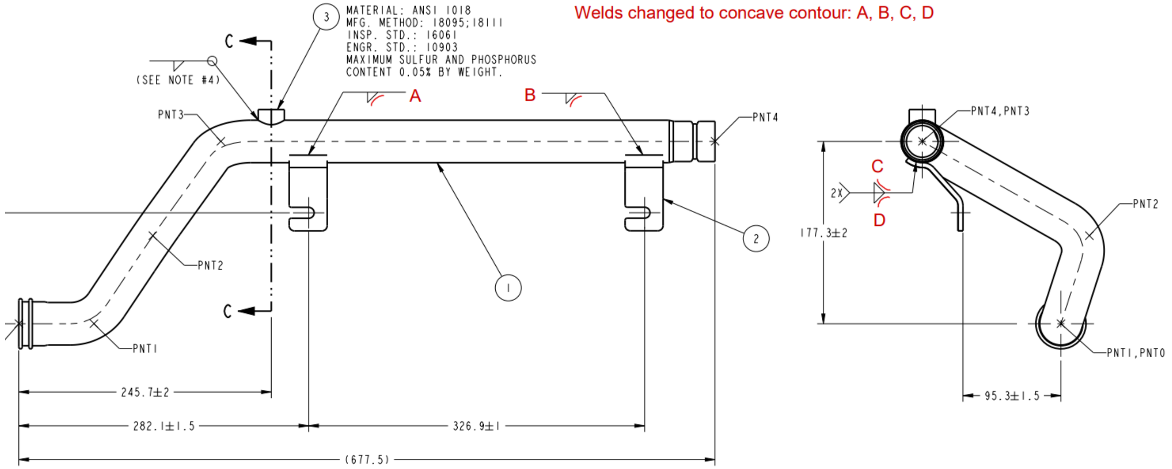
- Weld geometry is currently unspecified on both transfer tube prints
  - Reflected by inconsistent welds seen on new and failed samples
- Add weld geometry specifications to each tube based on ANSYS analysis
  - Determined the best weld geometry to reduce stress concentration (slide #_)
  - Short tube weld contour: Flat weld
  - Long tube weld contour: Concave weld



Welds changed to flat contour: A,B,C



Welds changed to concave contour: A, B, C, D



Next Steps and Recommendations

- Dimensional quality issues
  - 5575183 bracket out-of-tolerance dimensions, inform supplier
  - If fit is an issue once dimensions are fixed, evaluate print dimensions
- Weld quality issues
  - 4367122 supplier has not yet responded to SQIE, follow up
  - Have supplier evaluate weld application process that may cause quality issues
- Static/dynamic stress analysis
  - Repeat test cell strain gauge operation for part with dimensional quality issues and compare to initial results if needed to determine severity of these issues
  - Validate durability of 1.5 mm long tube bracket thickness change
    - Cost justify with quote from supplier, create CTR -> CR to make this change

Next Steps and Recommendations

- Stress concentration
  - Repeat ANSYS analysis for thinner 4367122 bracket to confirm best weld geometry
  - Create CTR -> CR for weld geometry change with analysis results, cost justify
- If significant failure still occurs after current solutions are implemented, implement step 3 additional welds as permanent solutions (slide #_)
  - ANSYS analysis (slide #_) shows that these weld additions reduce the concentrated stress seen on weld edges, particularly on the toe at these edges
  - If current solutions are not effective, this solution is likely to be cost justified
    - Continued failure leads to projected failure reduction from this solution to offset cost
    - Follow up with long tube supplier for added weld quote, finish cost justification

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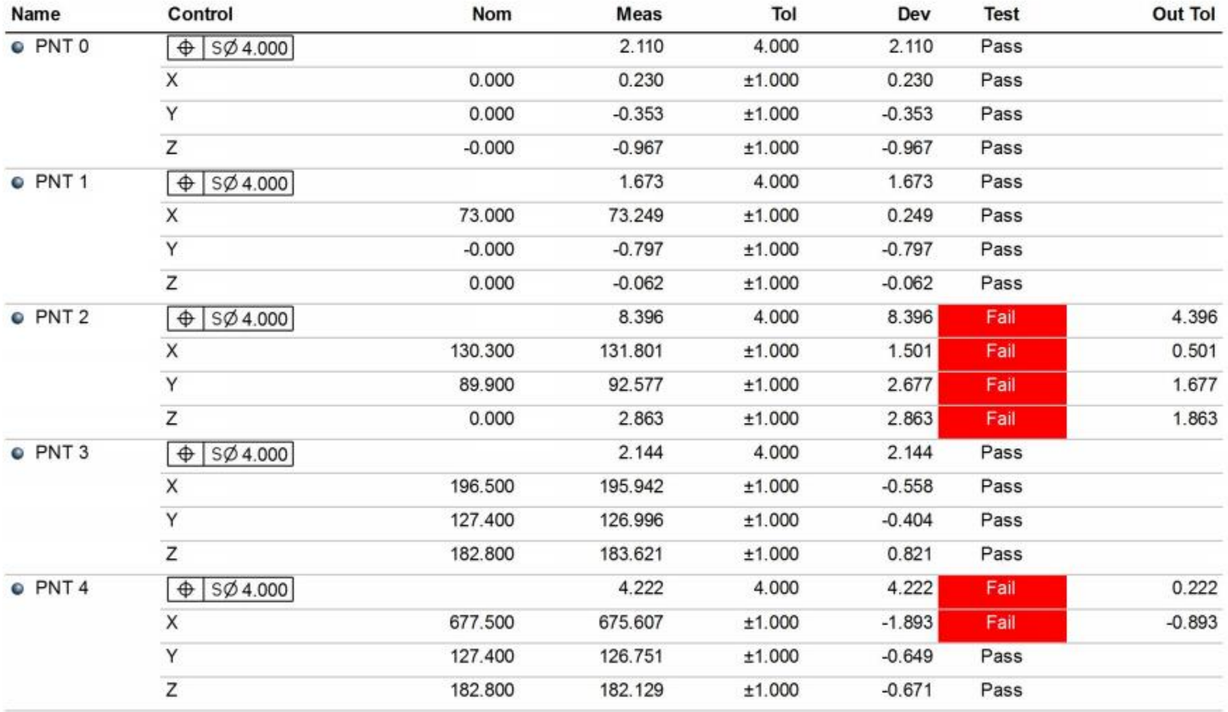
Appendix

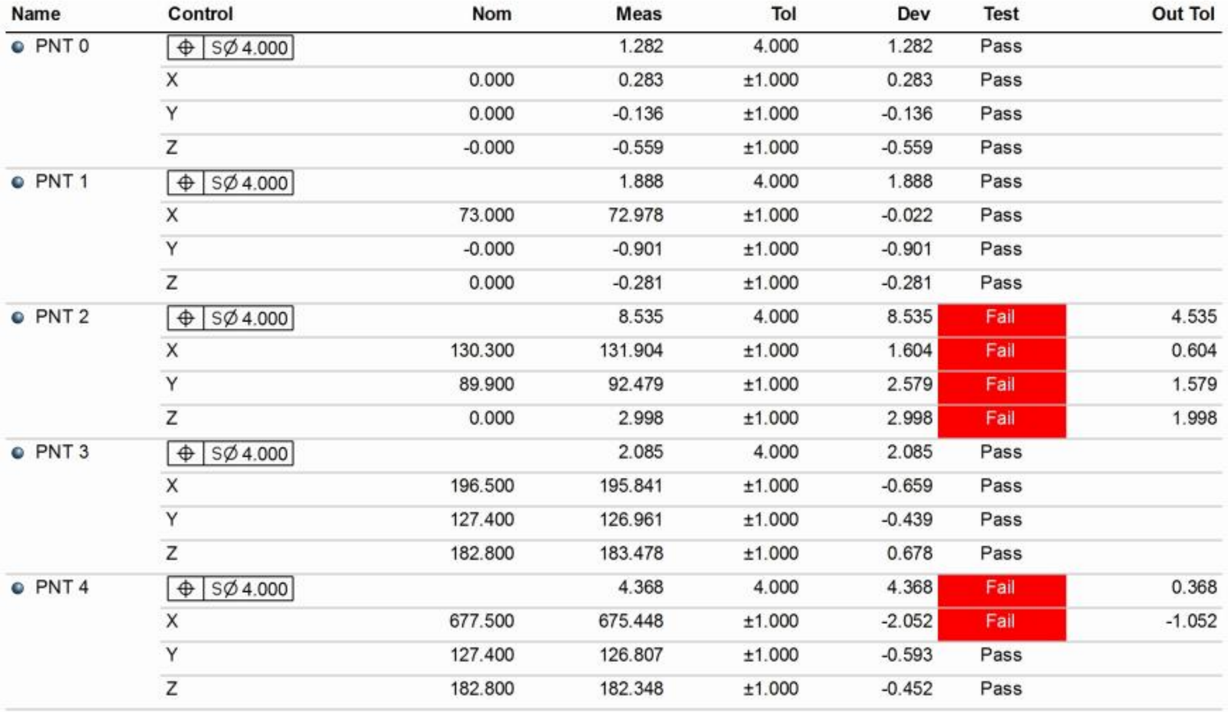
Intersection Point Position Measurements – 4367122

Sample #1:



Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
● PNT 0	⌖ SØ 4.000		2.110	4.000	2.110	Pass	
	X	0.000	0.230	±1.000	0.230	Pass	
	Y	0.000	-0.353	±1.000	-0.353	Pass	
	Z	-0.000	-0.967	±1.000	-0.967	Pass	
● PNT 1	⌖ SØ 4.000		1.673	4.000	1.673	Pass	
	X	73.000	73.249	±1.000	0.249	Pass	
	Y	-0.000	-0.797	±1.000	-0.797	Pass	
	Z	0.000	-0.062	±1.000	-0.062	Pass	
● PNT 2	⌖ SØ 4.000		8.396	4.000	8.396	Fail	4.396
	X	130.300	131.801	±1.000	1.501	Fail	0.501
	Y	89.900	92.577	±1.000	2.677	Fail	1.677
	Z	0.000	2.863	±1.000	2.863	Fail	1.863
● PNT 3	⌖ SØ 4.000		2.144	4.000	2.144	Pass	
	X	196.500	195.942	±1.000	-0.558	Pass	
	Y	127.400	126.996	±1.000	-0.404	Pass	
	Z	182.800	183.621	±1.000	0.821	Pass	
● PNT 4	⌖ SØ 4.000		4.222	4.000	4.222	Fail	0.222
	X	677.500	675.607	±1.000	-1.893	Fail	-0.893
	Y	127.400	126.751	±1.000	-0.649	Pass	
	Z	182.800	182.129	±1.000	-0.671	Pass	

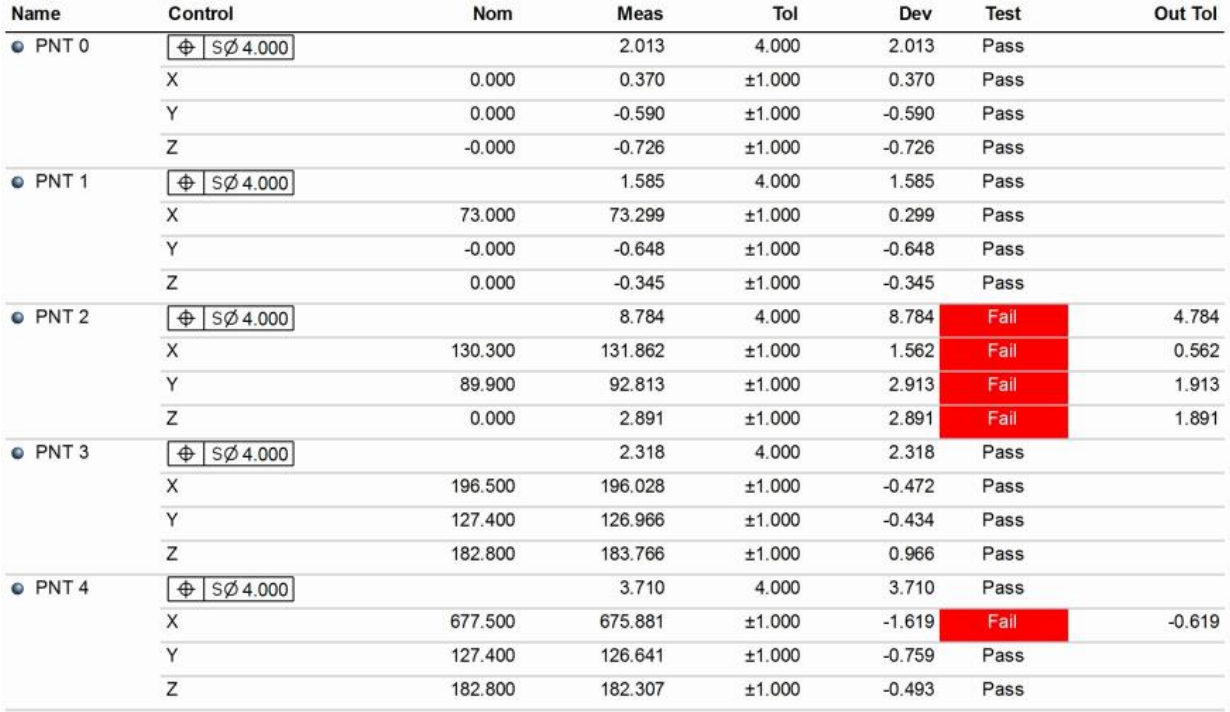
Sample #2:



Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
● PNT 0	⌖ SØ 4.000		1.282	4.000	1.282	Pass	
	X	0.000	0.283	±1.000	0.283	Pass	
	Y	0.000	-0.136	±1.000	-0.136	Pass	
	Z	-0.000	-0.559	±1.000	-0.559	Pass	
● PNT 1	⌖ SØ 4.000		1.888	4.000	1.888	Pass	
	X	73.000	72.978	±1.000	-0.022	Pass	
	Y	-0.000	-0.901	±1.000	-0.901	Pass	
	Z	0.000	-0.281	±1.000	-0.281	Pass	
● PNT 2	⌖ SØ 4.000		8.535	4.000	8.535	Fail	4.535
	X	130.300	131.904	±1.000	1.604	Fail	0.604
	Y	89.900	92.479	±1.000	2.579	Fail	1.579
	Z	0.000	2.998	±1.000	2.998	Fail	1.998
● PNT 3	⌖ SØ 4.000		2.085	4.000	2.085	Pass	
	X	196.500	195.841	±1.000	-0.659	Pass	
	Y	127.400	126.961	±1.000	-0.439	Pass	
	Z	182.800	183.478	±1.000	0.678	Pass	
● PNT 4	⌖ SØ 4.000		4.368	4.000	4.368	Fail	0.368
	X	677.500	675.448	±1.000	-2.052	Fail	-1.052
	Y	127.400	126.807	±1.000	-0.593	Pass	
	Z	182.800	182.348	±1.000	-0.452	Pass	

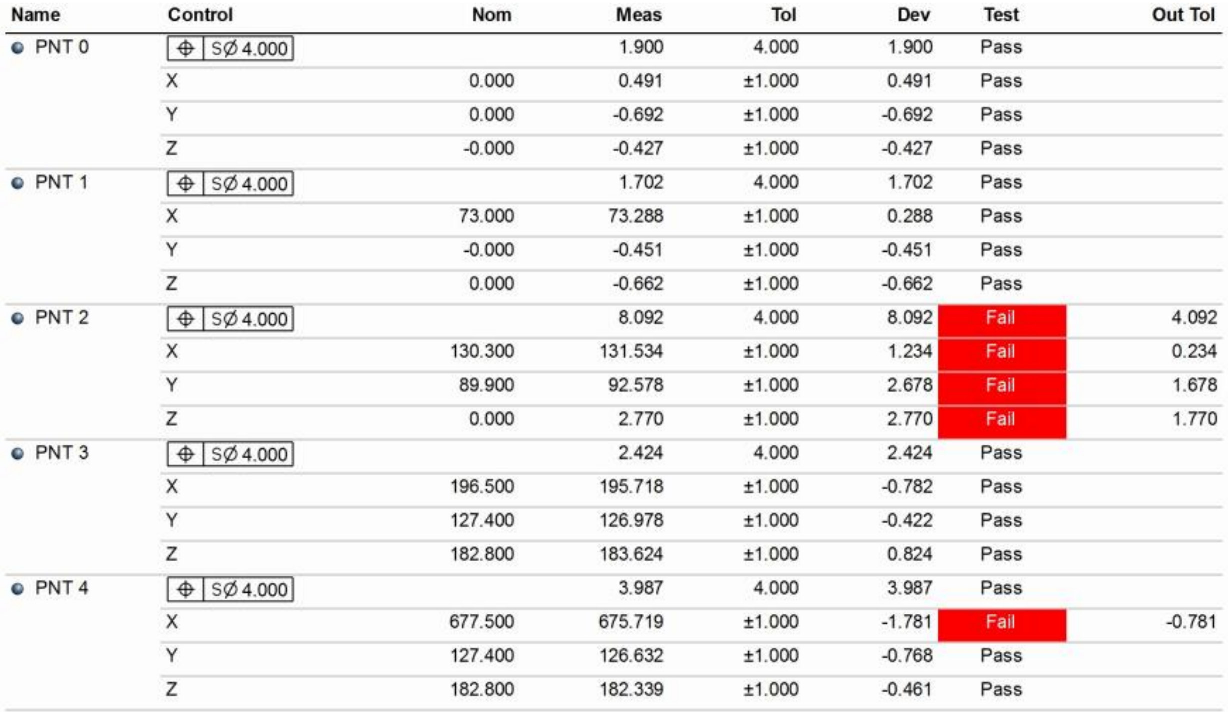
Intersection Point Position Measurements – 4367122

Sample #3:



Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
● PNT 0	⌖ SØ4.000		2.013	4.000	2.013	Pass	
	X	0.000	0.370	±1.000	0.370	Pass	
	Y	0.000	-0.590	±1.000	-0.590	Pass	
	Z	-0.000	-0.726	±1.000	-0.726	Pass	
● PNT 1	⌖ SØ4.000		1.585	4.000	1.585	Pass	
	X	73.000	73.299	±1.000	0.299	Pass	
	Y	-0.000	-0.648	±1.000	-0.648	Pass	
	Z	0.000	-0.345	±1.000	-0.345	Pass	
● PNT 2	⌖ SØ4.000		8.784	4.000	8.784	Fail	4.784
	X	130.300	131.862	±1.000	1.562	Fail	0.562
	Y	89.900	92.813	±1.000	2.913	Fail	1.913
	Z	0.000	2.891	±1.000	2.891	Fail	1.891
● PNT 3	⌖ SØ4.000		2.318	4.000	2.318	Pass	
	X	196.500	196.028	±1.000	-0.472	Pass	
	Y	127.400	126.966	±1.000	-0.434	Pass	
	Z	182.800	183.766	±1.000	0.966	Pass	
● PNT 4	⌖ SØ4.000		3.710	4.000	3.710	Pass	
	X	677.500	675.881	±1.000	-1.619	Fail	-0.619
	Y	127.400	126.641	±1.000	-0.759	Pass	
	Z	182.800	182.307	±1.000	-0.493	Pass	

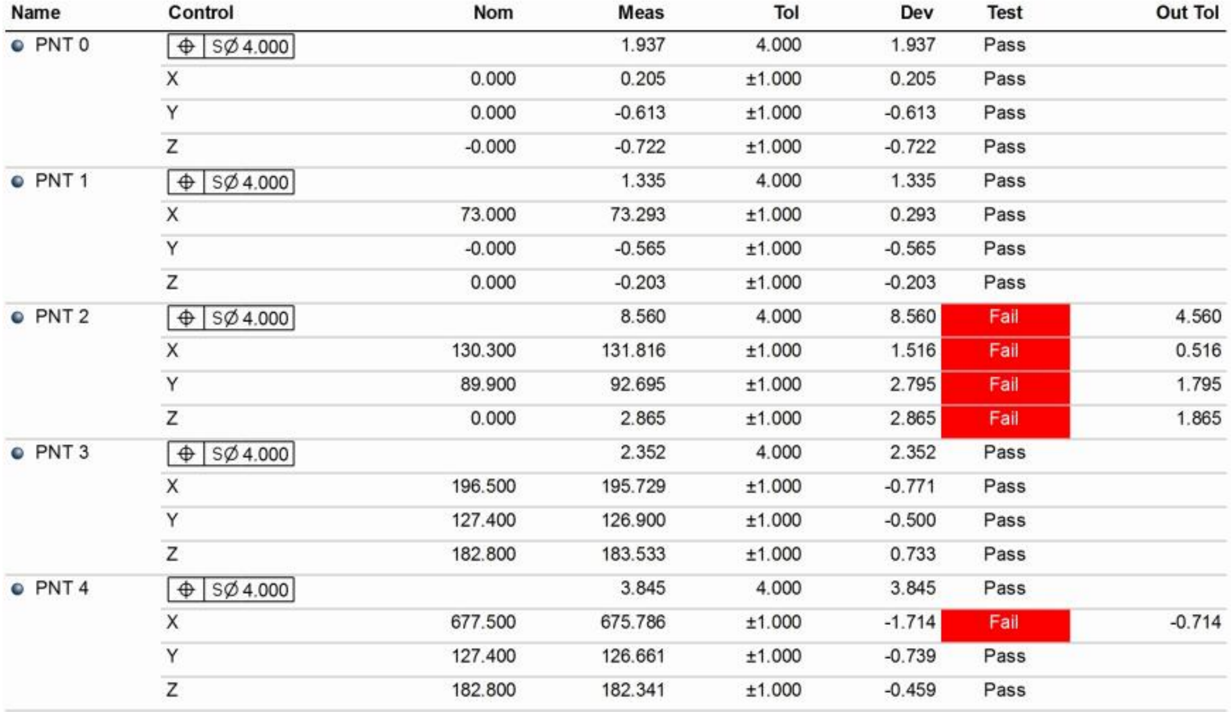
Sample #4:



Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
● PNT 0	⌖ SØ4.000		1.900	4.000	1.900	Pass	
	X	0.000	0.491	±1.000	0.491	Pass	
	Y	0.000	-0.692	±1.000	-0.692	Pass	
	Z	-0.000	-0.427	±1.000	-0.427	Pass	
● PNT 1	⌖ SØ4.000		1.702	4.000	1.702	Pass	
	X	73.000	73.288	±1.000	0.288	Pass	
	Y	-0.000	-0.451	±1.000	-0.451	Pass	
	Z	0.000	-0.662	±1.000	-0.662	Pass	
● PNT 2	⌖ SØ4.000		8.092	4.000	8.092	Fail	4.092
	X	130.300	131.534	±1.000	1.234	Fail	0.234
	Y	89.900	92.578	±1.000	2.678	Fail	1.678
	Z	0.000	2.770	±1.000	2.770	Fail	1.770
● PNT 3	⌖ SØ4.000		2.424	4.000	2.424	Pass	
	X	196.500	195.718	±1.000	-0.782	Pass	
	Y	127.400	126.978	±1.000	-0.422	Pass	
	Z	182.800	183.624	±1.000	0.824	Pass	
● PNT 4	⌖ SØ4.000		3.987	4.000	3.987	Pass	
	X	677.500	675.719	±1.000	-1.781	Fail	-0.781
	Y	127.400	126.632	±1.000	-0.768	Pass	
	Z	182.800	182.339	±1.000	-0.461	Pass	

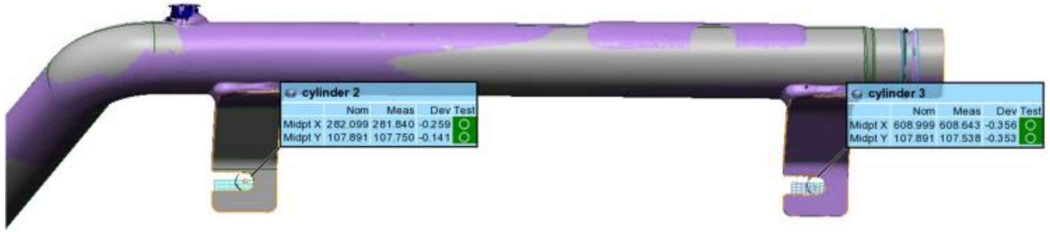
Intersection Point Position Measurements – 4367122

Sample #5:



Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
● PNT 0	⌖ SØ 4.000		1.937	4.000	1.937	Pass	
	X	0.000	0.205	±1.000	0.205	Pass	
	Y	0.000	-0.613	±1.000	-0.613	Pass	
	Z	-0.000	-0.722	±1.000	-0.722	Pass	
● PNT 1	⌖ SØ 4.000		1.335	4.000	1.335	Pass	
	X	73.000	73.293	±1.000	0.293	Pass	
	Y	-0.000	-0.565	±1.000	-0.565	Pass	
	Z	0.000	-0.203	±1.000	-0.203	Pass	
● PNT 2	⌖ SØ 4.000		8.560	4.000	8.560	Fail	4.560
	X	130.300	131.816	±1.000	1.516	Fail	0.516
	Y	89.900	92.695	±1.000	2.795	Fail	1.795
	Z	0.000	2.865	±1.000	2.865	Fail	1.865
● PNT 3	⌖ SØ 4.000		2.352	4.000	2.352	Pass	
	X	196.500	195.729	±1.000	-0.771	Pass	
	Y	127.400	126.900	±1.000	-0.500	Pass	
	Z	182.800	183.533	±1.000	0.733	Pass	
● PNT 4	⌖ SØ 4.000		3.845	4.000	3.845	Pass	
	X	677.500	675.786	±1.000	-1.714	Fail	-0.714
	Y	127.400	126.661	±1.000	-0.739	Pass	
	Z	182.800	182.341	±1.000	-0.459	Pass	

Bracket Position Measurements – 4367122



Sample #1:

Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
plane 2	Centroid Z	95.333	94.334	±1.500	-0.999	Pass	
plane 3	Centroid Z	95.247	95.880	±1.500	0.633	Pass	
cylinder 2	Midpoint X	282.099	281.840	±1.500	-0.259	Pass	
	Midpoint Y	107.891	107.750	±1.000	-0.141	Pass	
cylinder 3	Midpoint X	608.999	608.643	±2.500	-0.356	Pass	
	Midpoint Y	107.891	107.538	±1.000	-0.353	Pass	

Sample #2:

Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
plane 2	Centroid Z	95.333	94.350	±1.500	-0.983	Pass	
plane 3	Centroid Z	95.247	96.024	±1.500	0.777	Pass	
cylinder 2	Midpoint X	282.099	282.175	±1.500	0.076	Pass	
	Midpoint Y	107.891	107.961	±1.000	0.070	Pass	
cylinder 3	Midpoint X	608.999	608.920	±2.500	-0.079	Pass	
	Midpoint Y	107.891	107.640	±1.000	-0.251	Pass	

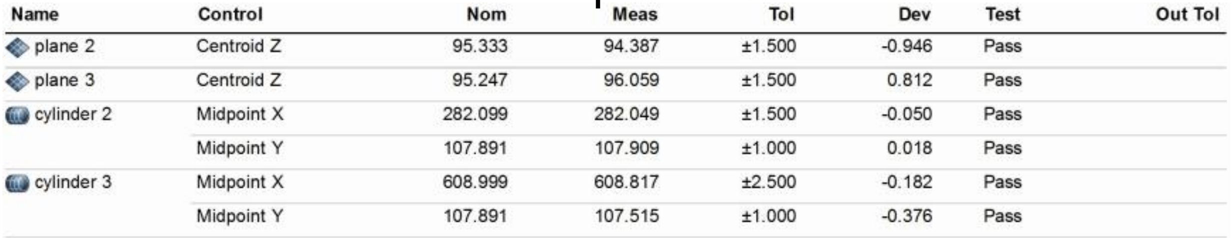
Sample #3:

Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
plane 2	Centroid Z	95.333	94.395	±1.500	-0.938	Pass	
plane 3	Centroid Z	95.247	95.983	±1.500	0.736	Pass	
cylinder 2	Midpoint X	282.099	282.191	±1.500	0.092	Pass	
	Midpoint Y	107.891	108.077	±1.000	0.186	Pass	
cylinder 3	Midpoint X	608.999	608.866	±2.500	-0.133	Pass	
	Midpoint Y	107.891	107.570	±1.000	-0.321	Pass	

Sample #4:

Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
plane 2	Centroid Z	95.333	94.484	±1.500	-0.849	Pass	
plane 3	Centroid Z	95.247	95.937	±1.500	0.690	Pass	
cylinder 2	Midpoint X	282.099	282.276	±1.500	0.177	Pass	
	Midpoint Y	107.891	107.866	±1.000	-0.025	Pass	
cylinder 3	Midpoint X	608.999	608.958	±2.500	-0.041	Pass	
	Midpoint Y	107.891	107.591	±1.000	-0.300	Pass	

Sample #5:



Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
plane 2	Centroid Z	95.333	94.387	±1.500	-0.946	Pass	
plane 3	Centroid Z	95.247	96.059	±1.500	0.812	Pass	
cylinder 2	Midpoint X	282.099	282.049	±1.500	-0.050	Pass	
	Midpoint Y	107.891	107.909	±1.000	0.018	Pass	
cylinder 3	Midpoint X	608.999	608.817	±2.500	-0.182	Pass	
	Midpoint Y	107.891	107.515	±1.000	-0.376	Pass	

5575183 Dimension Measurements

Sample 1:
https://cummins365-my.sharepoint.com/:b:/g/personal/ss378_cummins_com/Ecu_ZwnoxBtNs63gksUz_JIBUzLXVChwm714n6Kjjkmt_g?e=wY4VZ5

Sample 2:
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Sample 3:
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Sample 4:
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Sample 5:
https://cummins365-my.sharepoint.com/:b:/g/personal/ss378_cummins_com/EYrww6McgjVDp0-lnmytqHEBvmBhEbNQlXw2mNdl6HcdoQ?e=Rtes6P

3686409 Dimension Measurements

Sample 1:
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Sample 2:
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Sample 3:
https://cummins365-my.sharepoint.com/:b:/g/personal/ss378_cummins_com/EdgL19cFqSlErU9KCVMaukwBxBmofVNbYnGDRipE-3Q9jw?e=n9bbp0

Sample 4:
https://cummins365-my.sharepoint.com/:b:/g/personal/ss378_cummins_com/Eb50cbuMIg5Nm6CU2pbCSBkBtvk2ncGW-gjPbtxyCX_bmg?e=9l55wS