APA Mechanical Analysis

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Charge question

The completeness of the documentation of mechanical specifications, the 3D model and 2D drawings for standard and custom components, and the Compliance Office review of the design covering safety and proper application of design codes and standards.

Current Status of Analysis

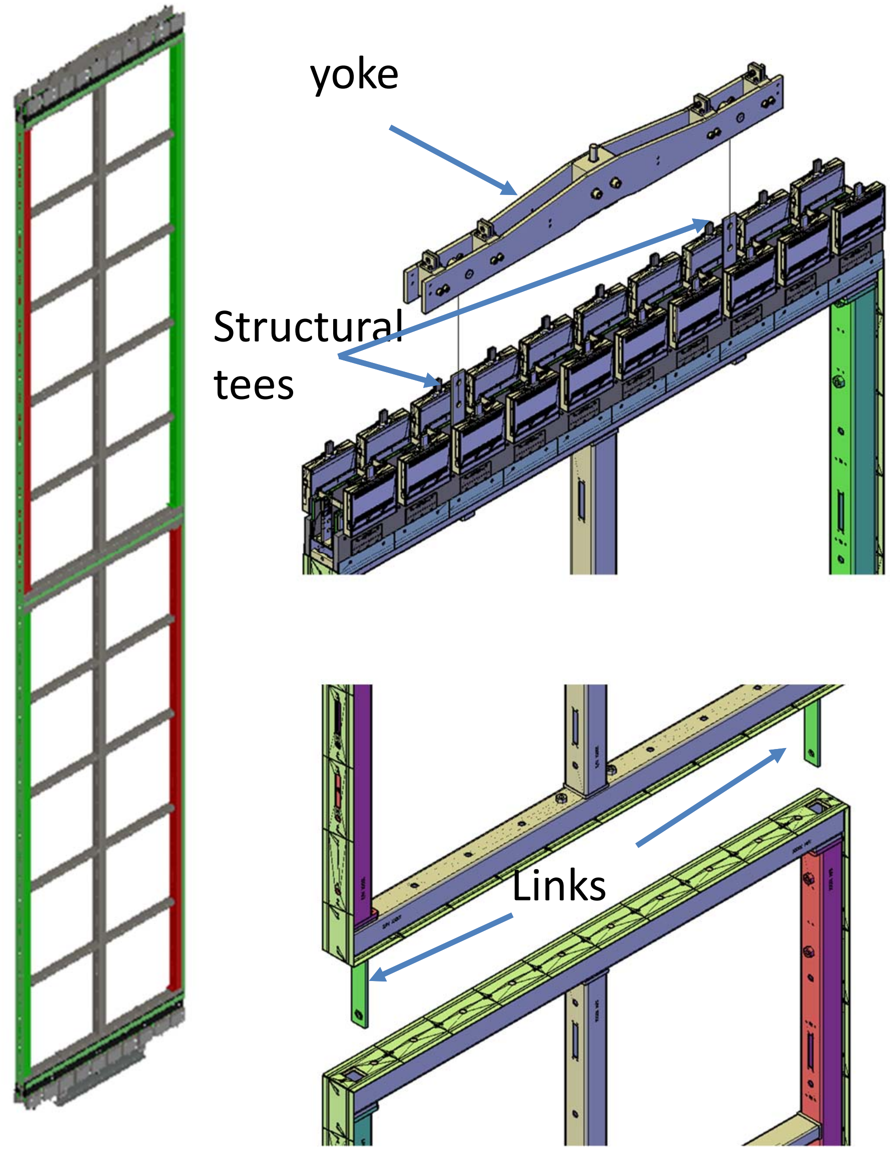
- APA Analysis plan is recently updated for review by the compliance office.
- APA analysis report
  - The APA frame is subject to a variety of load cases during the sequence of events from initial frame assembly at the factory to final cool-down in the installed state.
  - A total of 42 different FEA analysis have been run and subsequent analytical analyses using methods defined by AISC-360-16 and design guide 27 have been performed.
  - Several load cases need some additional work and the analysis of the yoke connection under thermal load still needs to be done.
  - The report is posted, but is not complete
- The Compliance Office report
  - The compliance office will provide their report several weeks after the final analysis report is complete.

The DUNE APA Analysis Plan can be found on EDMS at:
https://edms.cern.ch/document/2512420/2

The DUNE APA Analysis can be found at:
https://edms.cern.ch/document/2100877/2

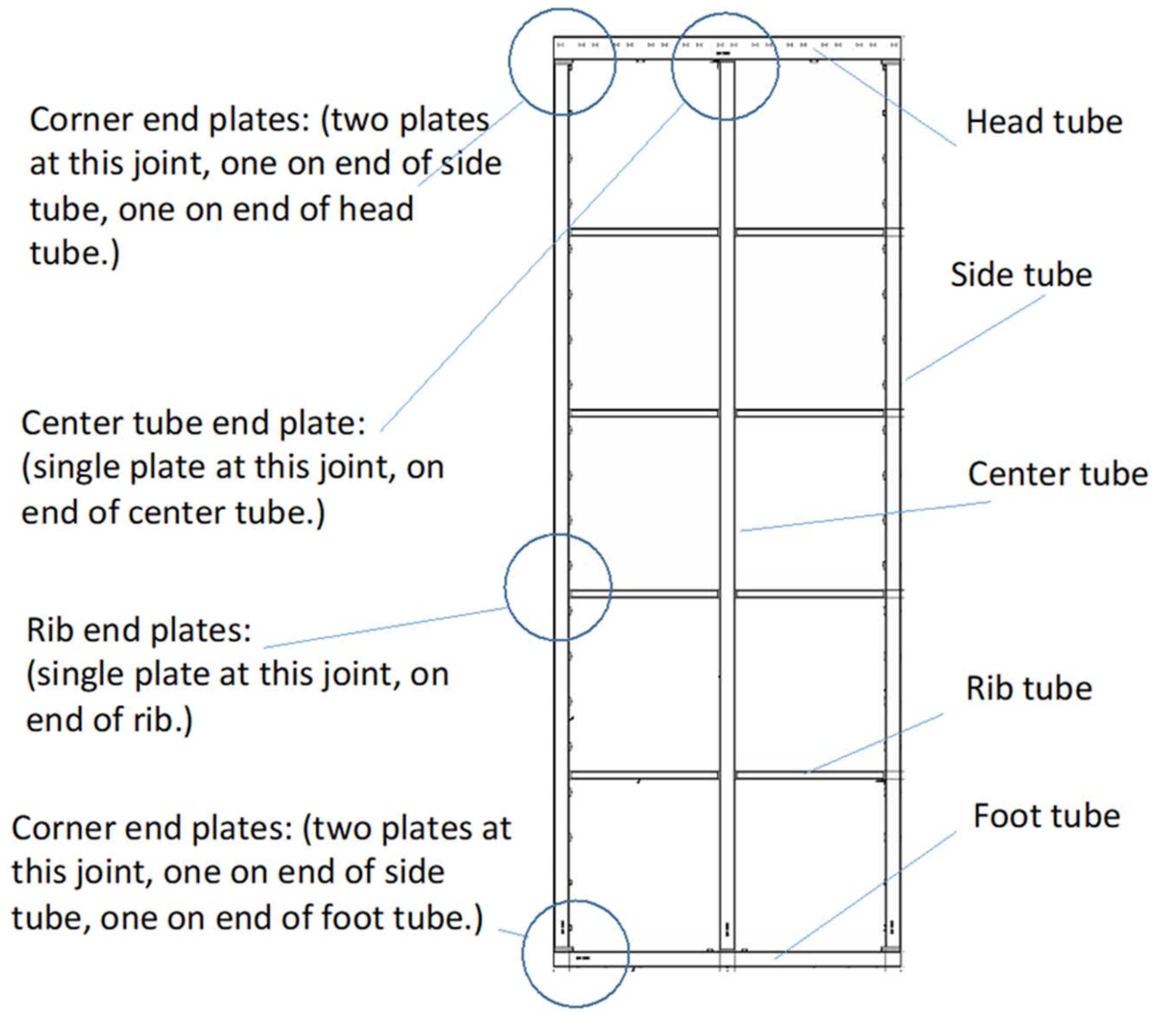
Introduction

- The analysis of the APA Frame and APA support system for all significant load cases will be presented.
- The load factors and resistance factors used for Load Factor Resistance Design (LFRD) method will be identified.
- The APA structural members, welded connections and bolted connections will be checked.

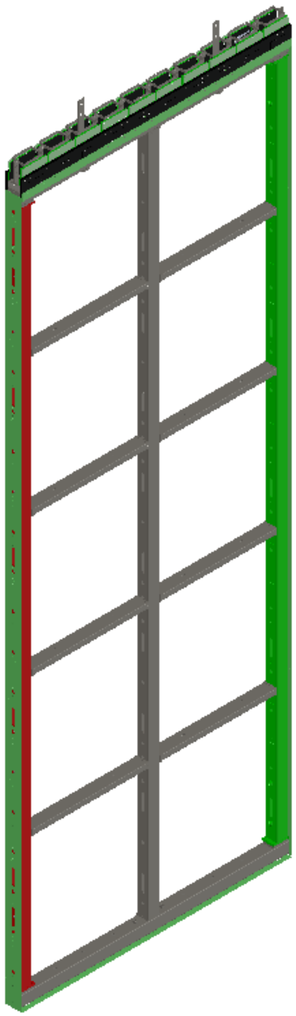


Integrated APA with yoke structural tees and links

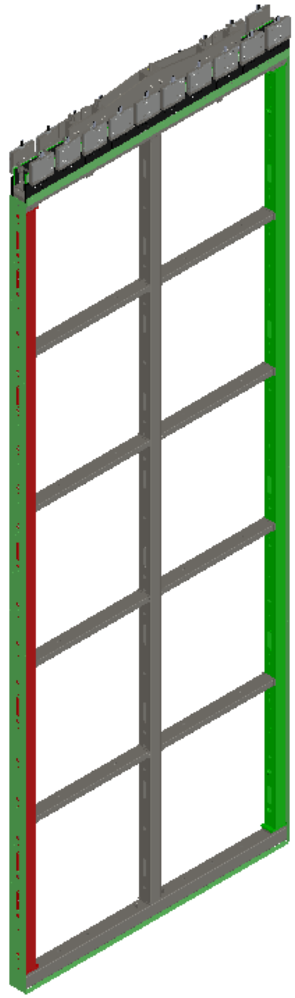
Nomenclature



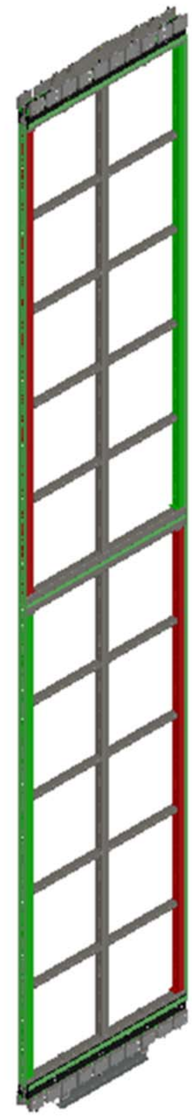
Nomenclature



Factory APA (Ships from factory)



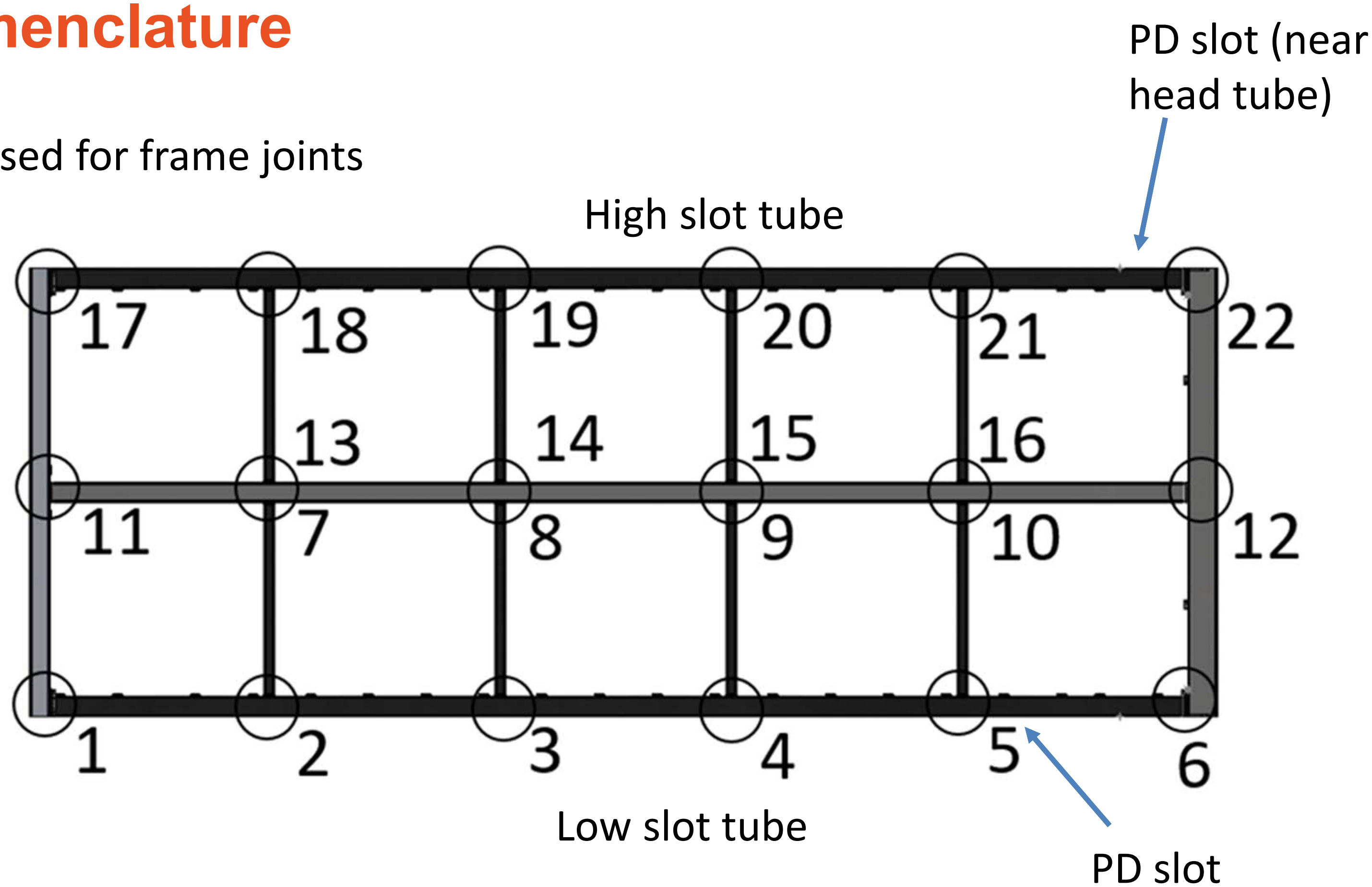
Integrated APA (PDs not shown)



APA Pair

Nomenclature

Labels used for frame joints



Design codes

- AISC's Specification for Structural Steel Buildings (AISC document 360-16)
- Design Guide 27: Structural Stainless Steel
- Load and Resistance Factor Design (LRFD) method for Stainless steel structures
  - Load Factor = 1.4
  - Load Factor = 1.0 for Transport cases
  - Member Resistance factor = 0.9
  - Weld nominal strength factor for shear = 0.6
  - Weld shear resistance factor = 0.55
  - Bolt resistance factor = .75

- JRC Science for Policy Report "Prospect for New Guidance in Design of FRP" as a guide for designing fiber reinforced plastics (FRP) structures
  - Safety factor of 3.75 for all effects of temperature, humidity, creep and material variation.

Load cases

Analysis Groups:

- Factory Preparation, Lifting, and Installation
- APA under Thermal load
- Static Transport cases
- Dynamic Transport cases

Note: Some cases defined in the Analysis Plan had the same boundary conditions and loading so they have been combined into one load case for analysis.

Analysis Load Case Number and Description	Analysis Plan #
Factory Preparation, Lifting, and Installation	
LC 1 – Bare frame lifting on edge	LC 1
LC 2 – APA supported in winding machine (upper two shafts)	LC 2
LC 3 - APA supported in winding machine (four corner shafts)	LC 3
LC 4 - APA supported in winding machine (lower two shafts)	LC 4
LC 5 - APA detector on the cart (gravity load downward parallel to the plane x-y)	LC 5
LC 6 - APA detector on the cart (gravity load downward normal to the plane x-y)	LC 6
LC 7 – Lifting on edge with solid support bars and protection	LC 7
LC 8 – Bottom APA hanging and lifting portrait orientation	LC 8
LC 9 – Bottom APA supported by the head tube	LC 9
LC 10 – Top APA in APA pair with protection	LC 10
LC 11 – Bottom APA installed	LC 11
LC 12 – Top APA installed	LC 12
APA under Thermal load	
LC 13 - 1 – Bottom installed during cooldown	LC-13
LC 13 - 2 – Top APA installed during cooldown	new
LC 14 - 1 – Bottom installed with 50% extra wire preload	LC 14
LC 14 - 2 – Top APA installed with 50% extra wire preload	new
Static Transport Cases	
LC 15 – APA Pair Installed in ASF	LCD 6-3
LC 16 – ASF Lifting	LCD 1
	LCD 4-2
	LCD 6-2
LC 17-1 through 10 – Rotation from 0° to 90° (10 cases)	LCD 4-3
	LCD 6-1
	LCD 7-1
LC 18-1 – Operational lowering in the Ross Shaft	LCD 5-1
	LCD 5-2
LC 18-2 – Accidental failure of the Ross shaft hoist	LCD 5-3
LC 19-1 - Unloading the APAs from the ASF 2xAPA	LCD 7-2
	LCD 8-2
LC 19-2 - Unloading the APAs from the ASF - Top APA remaining	LCD 8-1
LC 20-1 - Quasi-Static cases for road transport	LCD 2-1
	LCD 4-1
LC 20-2 - Quasi-Static cases for sea transport	LCD 3
Dynamic Transport Cases	
LCD 1-1 through 3 – Random Vibration Cases (vertical, lateral, transversal)	LCD 2-2
	LCD 4-1
LCD 2-1 through 3 – Sine Vibration (vertical, lateral, transversal)	LCD 2-3
	LCD 4-1
LCD 3-1 through 3 – Shock (vertical, lateral, transversal)	LCD 2-4
	LCD 4-1
LCD 4- Shock (response)	LCD 2-5
	LCD 4-1
LCD 5- Shock (drop)	new
APA Support System	
LSS1 - Support of the APA pair by the M20 rod, the yoke, and the structural tee	LSS1
LSS2 - Support of the bottom APA by the links and the M20 screw	LSS2

Masses and contingency of components

For the different load cases, the masses of various components need to be considered.

Table 1 Masses to be considered for load cases

Component ID	Description	Nominal Mass	Mass with contingency	Contingency
		[kg]	[kg]	[%]
[1]	APA frame structure only	315.5	322.0	2.0
[2]	Upper/Lower APA with four wire layers (highest)	464.9	481.1	3.5
[3]	Upper/Lower Factory APA	492.3	510.0	3.6
[4]	Integrated APA Assembly	631.0	654.5	3.7
[5]	APA protection	74.0	81.4	10.0
[6]	Winder support bars	81.3	82.9	2.0
[7]	Yoke top	60.4	63.5	5.0
[8]	FC support (bottom yoke)	15.8	17.4	10.0
[9]	APA to APA link	2.8	3.1	10.0
[10]	Side tube CE cables	62.9	74.5	20.0
[11]	CE box protection	8.8	11.0	25.0
[12]	FC latches top	8.8	13.3	50.0
[13]	FC latches bottom	8.8	13.3	50.0
[14]	Tie bars	2.3	2.1	10.0
[15]	FC bottom	53.6	58.9	10.0
[16]	FC top	53.6	58.9	10.0
[17]	Edge and foot alignment pins (mass for APA pair)	0.3	0.3	10.0
[18]	Clevis	2.5	3.1	25.0
[19]	Conduit	17.2	18.1	25.3

Loads applied to each load case

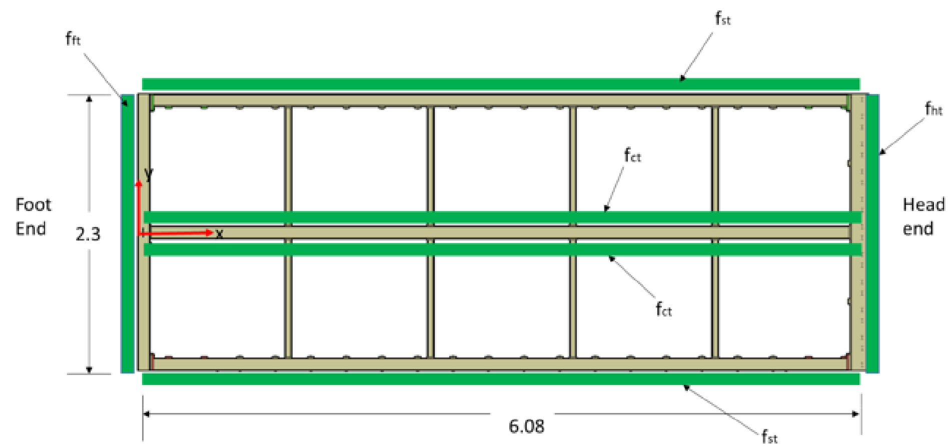
Table 2 Mass application to each load case

Load case ID	Component ID
LC 1	[1]
LC 2,3,4	[2]+[6]
LC 5,6	[3]+[5]+[6]-[19]
LC 7	[3]+[5]+[6]-[19]
LC 8	[4]+[5]-[7]+[8]+[18]
LC 9	[4]+[5]-[7]+[18]
LC 10	2*([4]+[5]-[7])+[8]+[9]+((14/22)*[10])+11+17
LC 11	[4]-[7]+[8]+[11]+[13]+[14]+[15]+[17]/2
LC 12	2*([4]-[7])+[8]+[9]+(14/22)*[10]+[11]+[13]+[14]+[15]+[17]
LC 13 -1,2	[4]-[7]+[8]+[11]+[13]+[14]+[15]+[17]/2
LC 14 - 1,2	[4]-[7]+[8]+[11]+[13]+[14]+[15]+[17]/2
LC 15	[3]+[5] (591.4 kg w/ 4.4 % conting.)
LC 16	[3]+[5] (591.4 kg w/ 4.4 % conting.)
LC 17-1,2,3 … 10	[3]+[5] (591.4 kg w/ 4.4 % conting.)
LC 18-1	[3]+[5] (591.4 kg w/ 4.4 % conting.)
LC 18-2	[3]+[5] (591.4 kg w/ 4.4 % conting.)
LC 19-1	[3]+[5] (591.4 kg w/ 4.4 % conting.)
LC 19-2	[3]+[5] (591.4 kg w/ 4.4 % conting.)
LC 20-1	[3]+[5] (591.4 kg w/ 4.4 % conting.)
LC 20-2	[3]+[5] (591.4 kg w/ 4.4 % conting.)
LCD 1-1,2,3	[3]+[5] (591.4 kg w/ 4.4 % conting.)
LCD 2-1,2,3	[3]+[5] (591.4 kg w/ 4.4 % conting.)
LCD 3-1,2,3	[3]+[5] (591.4 kg w/ 4.4 % conting.)
LCD 4	[3]+[5] (591.4 kg w/ 4.4 % conting.)

Application of masses carried by the Frame

- Mass of many components like boards are distributed on the frame.
- This load is assigned to each frame member
- The summation assigned load is checked against the summation of the component loads

LC -2, 3 and 4 –Factory APA supported in the winding machine.



Distributed and point masses on APA frame tubes - LC 2,3,4			
		With contingency	
Parameter	**Description**	**Un-factored**	**Factored**
fft	Mass on foot tube	7.97	11.16
fst	Mass on single side tube	30.20	42.28
fct	*Mass on single surface of center tube	18.30	25.62
fht	Mass on head tube	29.25	40.95
Fpd	Mass of PD rails (Comes from model)	25.00	35.00
Fws	Mass of winder support bars (Comes from model)	82.93	116.10
mframe	Mass of bare frame (Comes from model)	321.85	450.59
mtotal	Mass of factory APA	564.00	789.60
mtotal	[2]+[6]	564.00	789.60
*Note: The total mass on the center tube =2*fct			

Sum of mass assigned to frame

Sum of component loads

Wire Load carried by frame

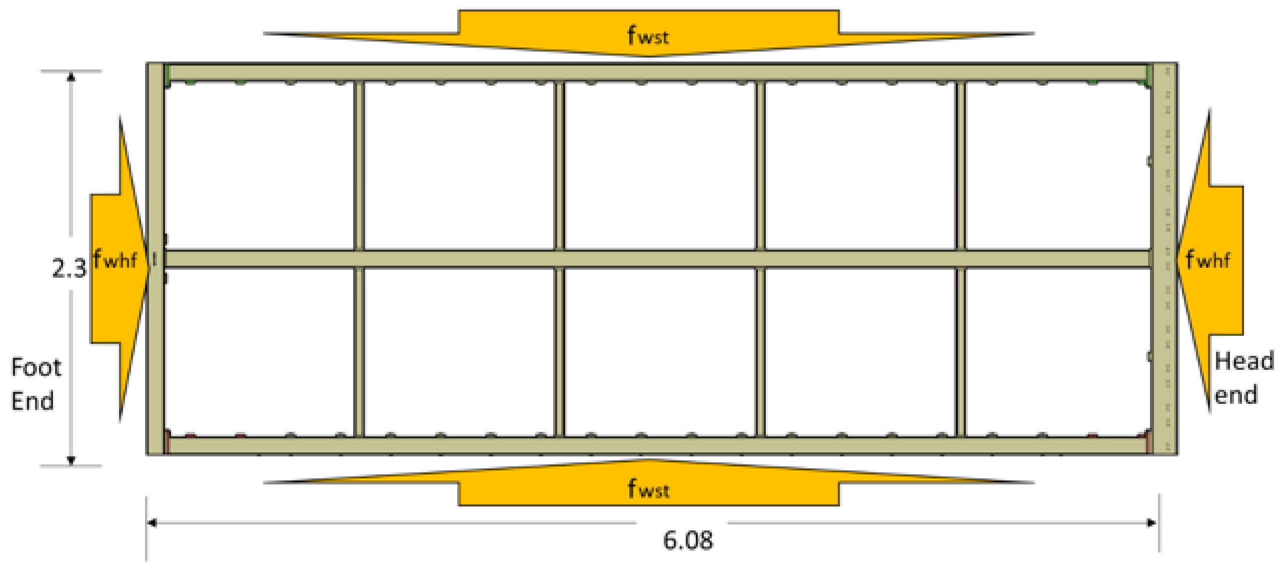


Figure 11: Wire preload on APA frame.

Wire load (6.5N)

$$f_{wst} = 16104 * N \; (per\ side\ tube)$$

$$f_{whf} = 29284 * N \; (per\ head\ or\ foot\ tube)$$

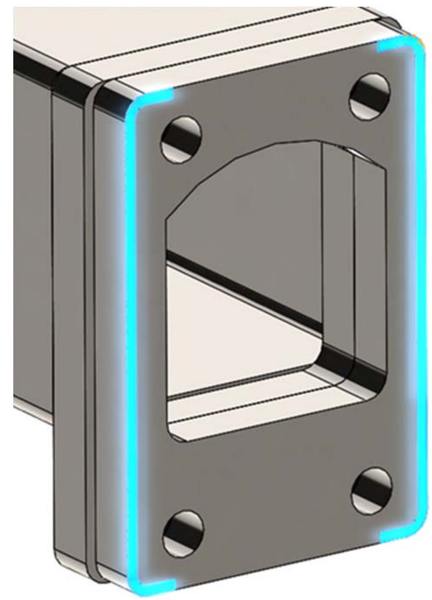
Includes 1.4 load factor

FEA Model

- A 3D representative model was built and Finite Element Analysis (FEA) was used to evaluate the frame.
- Primary software was ANSYS Simulation.
- ANSYS TET10 and HEX20 elements were used.
- Stresses in frame members were calculated by FEA
- Forces and moments on the joints were extracted from the FEA for use in code calculations for bolts and welds.
- Buckling was checked for all frame members.

Analysis of welded connections

- The weld joints are identified and reported by their joint location.
- There are four different types of welds
  1. Pad to head or foot tube
  2. Endcap to side tube
  3. Endcap to center tube
  4. Endcap to ribs
- Forces and moments on each joint were pulled from the FEA
- The weld stresses were calculated for each weld joint per the AISC -360-16 code.
- The resistance factor of .55 for welds from Design Guide 27: Structural Stainless Steel was used.



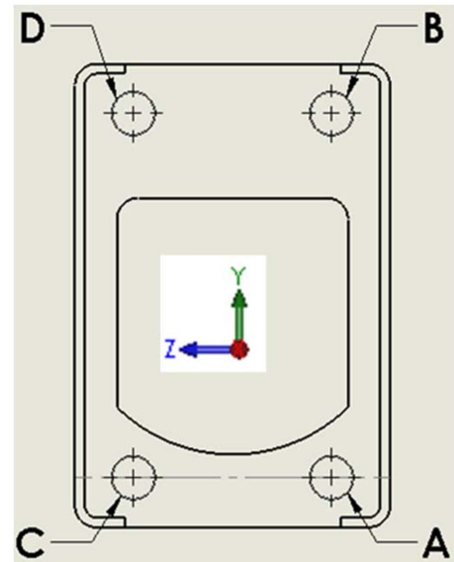
View of pad to head tube weld. Head tube not shown.

Analysis of welded connections

- The contribution of stresses from each of the 3 forces and 3 moments applied to the joint was used to determined the contribution to stress from each.
- The stresses from each force and moment are summed directly or vectorially (as appropriate) to arrive at the maximum value of force per unit length applied to the weld (N/m).

Analysis of bolted connections

- Individual bolts were labeled using the joint and bolt locations with respect to the Coordinate system
- Forces and moments on each joint were pulled from the FEA
- The tensile and shear forces were calculated for each bolt for each load case
- The available strengths of the M10 and M12 bolts were determined based on bolt size and materials (A2 Class 70 304 SS bolts and 0.75 resistance factor)
- Note: It is not necessary to evaluate combined stresses because the shear loads never exceed 30% of the available strengths. (See User Note in Section J3.7)



Frame stresses for Factory, Lifting, and Installation cases

Results from FEA

In some cases, the FEA stresses in joint 11 are higher than the available stress. The available stress is intended for use with analytical methods defined in AISC and not for FEA checks. In cases with high localized FEA stresses, an analytic check was done. See page 21 and Appendix 15.

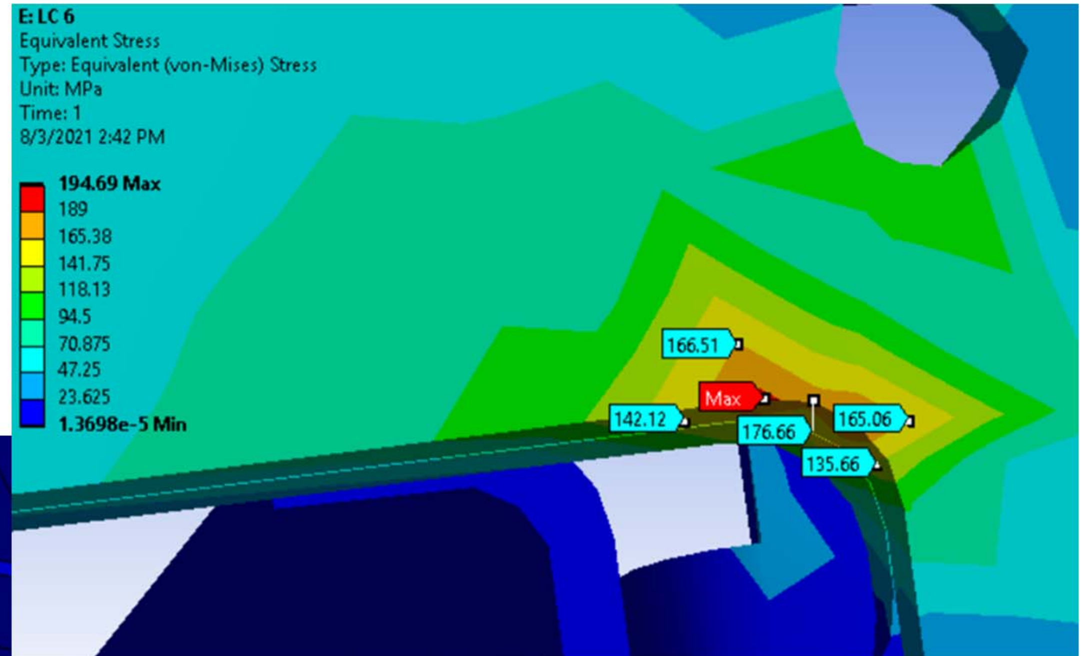
Case	Maximum Von Mises Stress (MPa)	Available Stress (MPa)	Utilization Ratio
LC 1	112.48	189	0.60
LC 6	176.66*	189	0.93
LC 8	180.42	189	0.95
LC 9	87*	189	0.46
LC 10	164.8	189	0.87
LC 11	187.2	189	0.99
LC 12	166.9	189	0.88

*stress artifacts are ignored (see appendix 6)

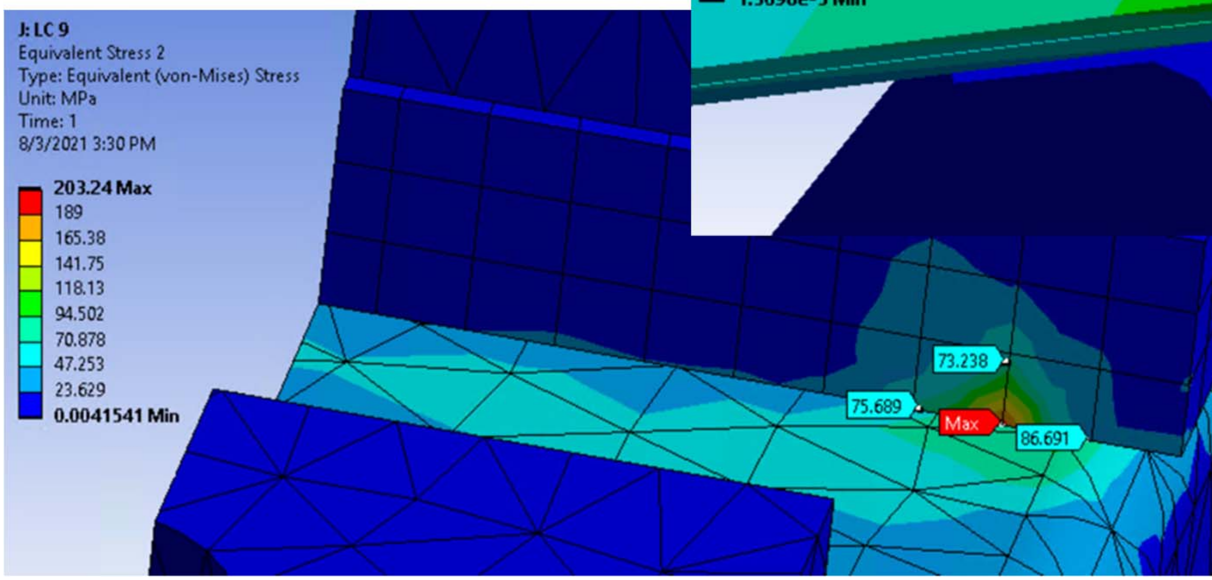
LC 11 Highest stress for cases checked with FEA. UR<1 is ok.

Frame stresses for Factory, Lifting, and Installation cases

Examples of FEA singularities that are ignored



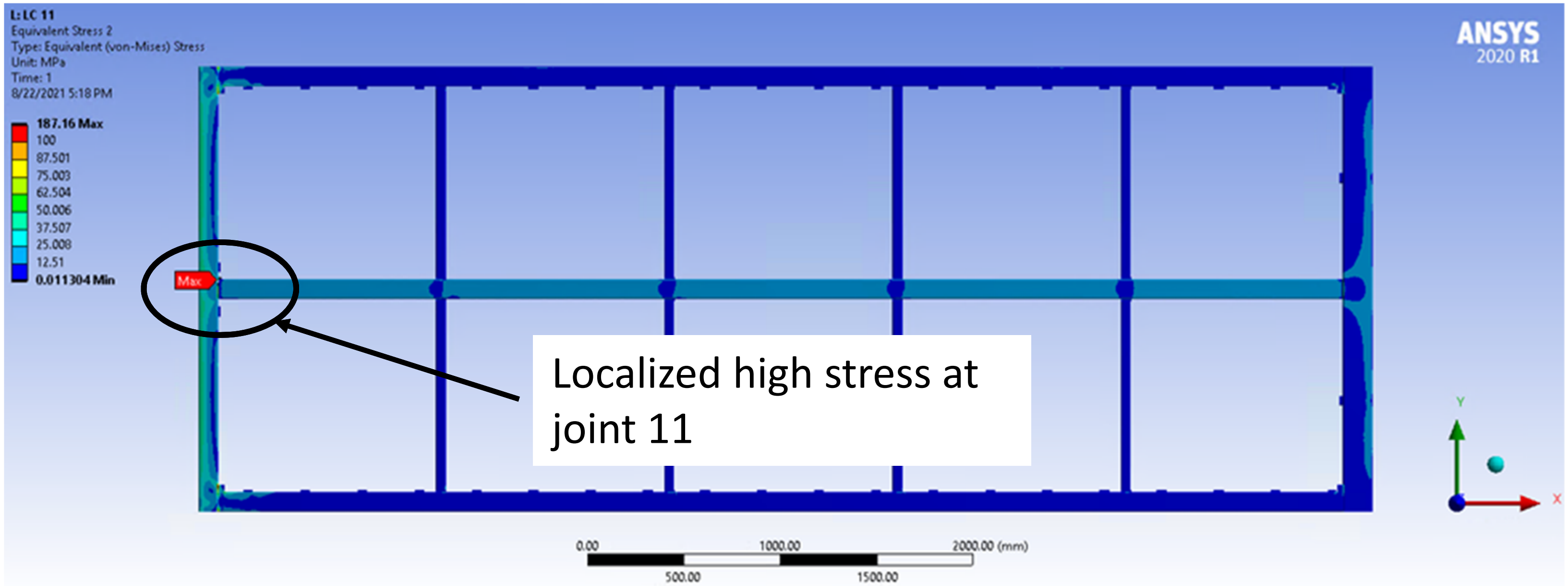
LC 6 singularity on edge of PD slot cutout



LC 9 Singularity on corner of joint 11 endcap

Frame stresses for Factory, Lifting, and Installation cases

Results from FEA



Stress plot for load case 11

Frame stresses for Factory, Lifting, and Installation cases

Results from analytical method - 360-16 AISC Chapter K HSS-to-HSS truss connection

The truss connection method is intended for welded vs. bolted connections.
The wire load is putting the joint 11 in compression and this compressive load is driving the utilization ratio. It is expected that the a bolted joint and welded joint under compression will experience similar stresses.

LFRD				
Load case number	Axial Force [kN]	Bending Moment y [N-m]	Bending Moment z [N-m]	LFRD - UR
LC 2	15.8	0.9	592	0.24
LC 3	15.8	1.2	757.7	0.29
LC 4	15.8	0.6	596.9	0.24
LC 5	15.8	1.4	884	0.33
LC 7	15.8	1.3	-590.1	0.24

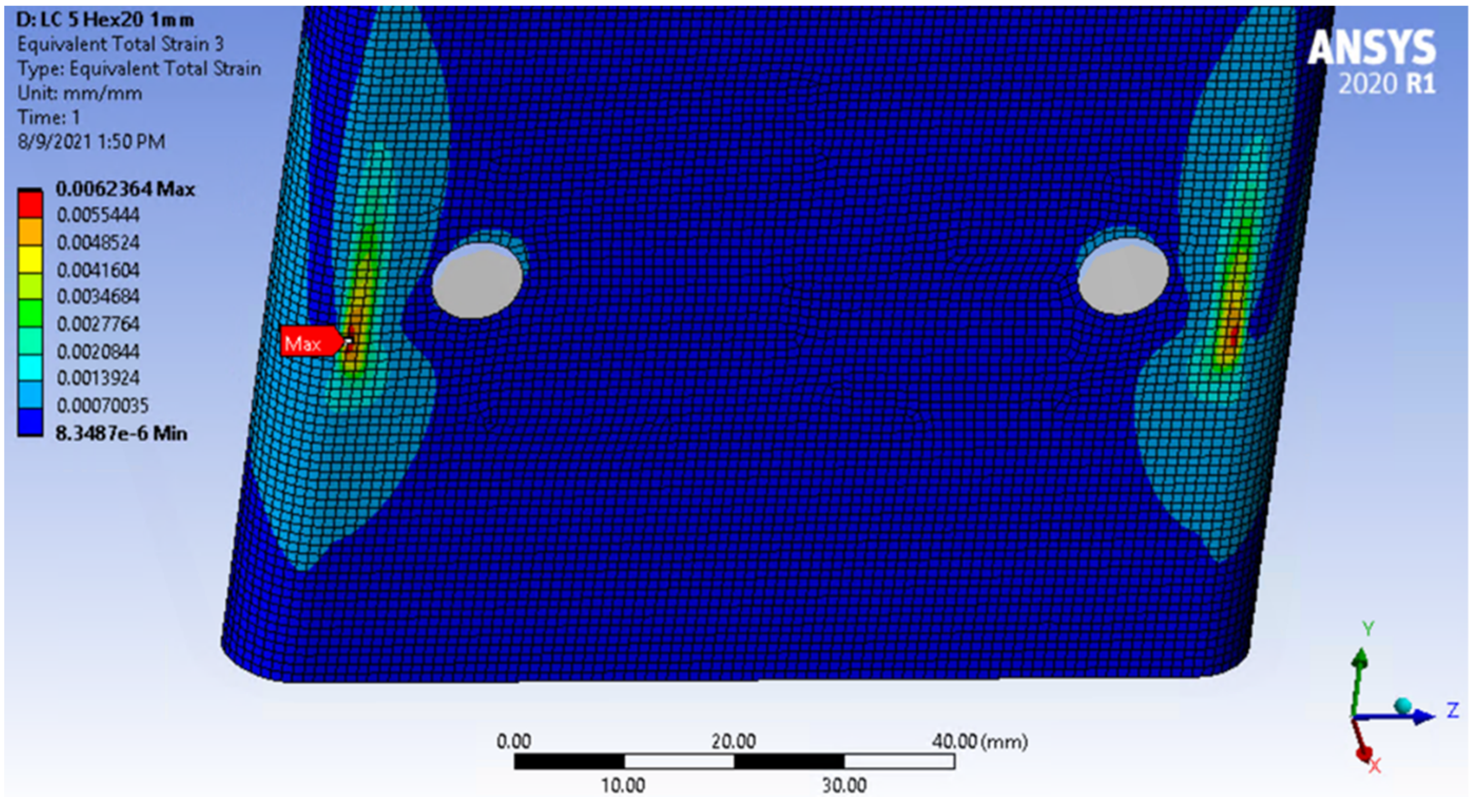
Highest Utilization Ratio (UR). For a welded connection, a UR under 1 is ok.

Note: Load Case 5 has the highest stress in joint 11 and was studied in more detail. See Appendix 15.

Frame stresses for Factory, Lifting, and Installation cases

Elastic plastic analysis of Joint 11 for the most highly stressed case, LC 5

The strain on the inside radius of the foot tube is calculated by elastic plastic analysis to be 0.6%. Annex C of Eurocode EN1993-1-5 section C.8 recommends a limiting value of principle strain of 5% for regions. Annex C gives guidance on the use of FE-methods



Total strain plot of Joint 11 for load case 5

Bolt results for Factory, Lifting, and Installation cases

M12 bolts with Maximum Axial force for each case

Case Number	Description	Jo int	Bolt	Bolt Type	Axial Force (N)	Shear Force (N)	Available Axial to Calculated	Available Shear to Calculated
LC 1	Maximum M12 Axial	22	C	M12	1500	52	20.9	368.5
LC 2	Maximum M12 Axial	17	A	M12	7500	886	4.2	21.4
LC 3	Maximum M12 Axial	17	A	M12	8000	377	4	50.5
LC 4	Maximum M12 Axial	17	A	M12	7600	807	4.2	23.6
LC 5	Maximum M12 Axial	17	A	M12	8600	335	3.7	56.7
LC 6	Maximum M12 Axial	17	C	M12	4400	1000	7.2	19
LC 7	Maximum M12 Axial	1	B	M12	7000	562	4.5	33.8
LC 8	Maximum M12 Axial	1	B	M12	5500	663	5.8	28.7
LC 9	Maximum M12 Axial	1	B	M12	4300	546	7.3	34.8
LC 10	Maximum M12 Axial	1	B	M12	6100	673	5.2	28.2
LC 11	Maximum M12 Axial	1	B	M12	6000	659	5.3	28.8
LC 12	Maximum M12 Axial	1	B	M12	6000	665	5.3	28.6

Load case 5 has the highest axial load. A ratio > 1 is ok.

Note: Maximum shear force for of all cases and joints is less than 30% of available, Therefore it is not necessary to consider combined loading. (See User Note in Section J3.7)

Bolt results for Factory, Lifting, and Installation cases

M10 bolts with Maximum Axial force for each case

Case Number	Description	Joint	Bolt	Bolt Type	Axial Force (N)	Shear Force (N)	Available Axial to Calculated	Available Shear to Calculated
LC 1	Maximum M10 Axial	18	A	M10	2300	73	9.5	181.7
LC 2	Maximum M10 Axial	12	A	M10	7300	220	3	60
LC 3	Maximum M10 Axial	12	A	M10	7400	236	3	56
LC 4	Maximum M10 Axial	12	A	M10	7400	226	3	58.4
LC 5	Maximum M10 Axial	12	A	M10	8000	272	2.8	48.5
LC 6	Maximum M10 Axial	12	B	M10	4900	324	4.5	40.7
LC 7	Maximum M10 Axial	12	B	M10	7800	113	2.8	116.7
LC 8	Maximum M10 Axial	12	A	M10	4300	5	5.1	2490.2
LC 9	Maximum M10 Axial	12	A	M10	4900	2	4.5	7924.4
LC 10	Maximum M10 Axial	12	A	M10	2900	31	7.5	421.3
LC 11	Maximum M10 Axial	12	A	M10	4500	8	4.9	1761.2
LC 12	Maximum M10 Axial	12	A	M10	3000	30	7.3	442.5

Load case 5 and 7 have the highest axial load and are ok

Note: Maximum shear force for of all cases and joints is less than 30% of available, Therefore it is not necessary to consider combined loading. (See User Note in Section J3.7)

Weld results for Factory, Lifting, and Installation cases

Case	Weld Location (by Joint Number)	Available Strength to Calculated
LC 1	6	17.9
LC 2	22	3.9
LC 3	22	3.8
LC 4	22	3.9
LC 5	22	3.5
LC 6	6	7.1
LC 7	6	3.8
LC 8	17	6.1
LC 9	22	6.4
LC 10	1	5.2
LC 11	1	5.4
LC 12	1	5.3

Load Case 5 has the highest weld load and is ok.

Wire Tension results for Factory, Lifting, and Installation cases

Case	Max 0° (N)	Max -36° (N)	Max +36° (N)	Minimum Safety Margin
LC 1	6.51	7.09	7.16	2.71
LC 2	6.48	7.56	7.10	2.57
LC 3	6.51	7.46	7.35	2.60
LC 4	6.48	7.58	7.09	2.56
LC 5	6.48	7.68	7.13	2.53
LC 6	6.83	8.31	8.31	2.34
LC 7	6.47	7.60	7.94	2.44
LC 8	6.48	6.54	6.55	2.96
LC 9	6.44	6.60	6.59	2.94
LC 10	6.49	6.65	6.72	2.89
LC 11	6.48	6.53	6.56	2.96
LC 12	6.49	6.62	6.69	2.90

LC6 has the minimum safety margin and is ok

Note: Minimal safety margin is based on a design strength of 19.4N (actual minimum yield is 23.3N) divided by Maximum tension.

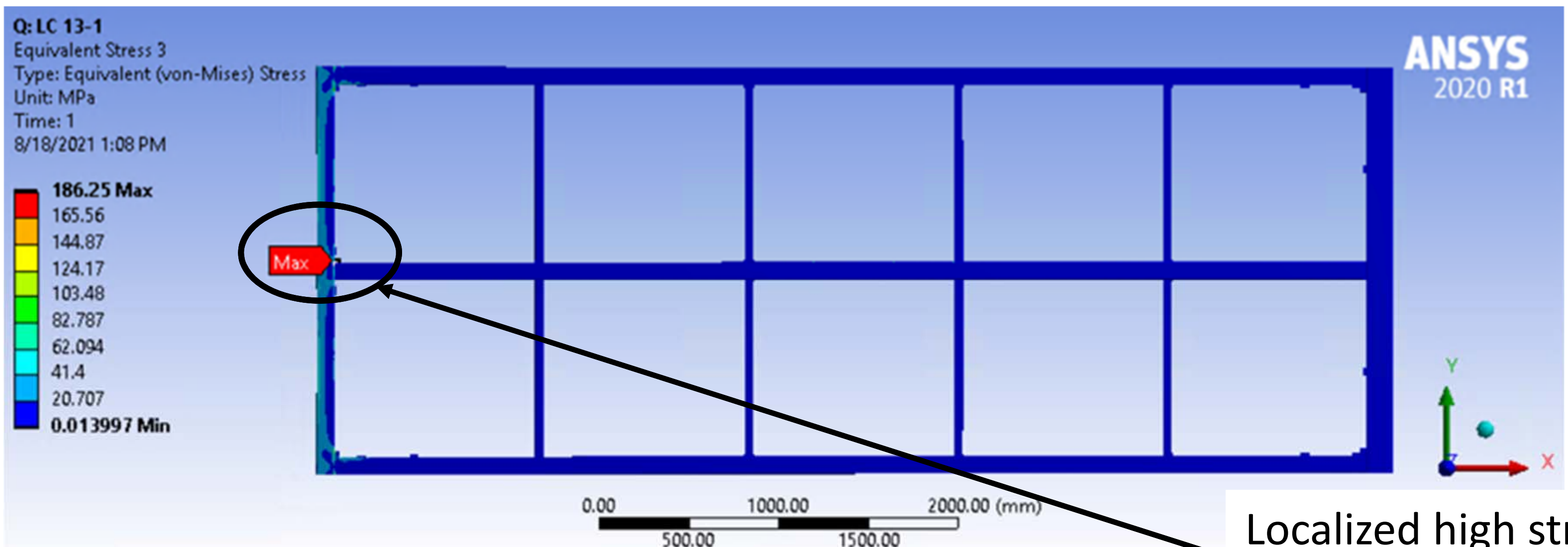
Frame Stresses for APA under Thermal load

Results from FEA

For cases LC14 -1 and LC14-2 an analytic check will be done.

Case	Maximum Von Mises Stress (MPa)	Available Stress (MPa)	Utilization Ratio
13-1	186.3	189.0	0.99
13-2	161.8	189.0	0.86

Load case 13-1 has the highest peak stress for cases checked with FEA.



Localized high stress at joint 13-1

Stress plot for load case 13-1

Frame Stresses for APA under Thermal load

Results from analytical method - 360-16 AISC Chapter K HSS-to-HSS truss connection

Load case number	Axial Force [kN]	Bending Moment y [N-m]	Bending Moment z [N-m]	LFRD - UR
LC 14-1	23.9	0	-33.5	0.12
LC 14-2	22.1	-1.1	-50.2	0.12

LC 14-1,and -2 have a UR that is less than 1

Bolt Results for APA under Thermal load

M12 and M10 bolts with Maximum Axial force for each case

Case Number	Description	Joint	Bolt	Bolt Type	Axial Force (N)	Shear Force (N)	Available Axial to Calculated	Available Shear to Calculated
LC 13-1	Maximum M12 Axial	1	B	M12	6210.9	562.0	5.1	33.8
LC 13-2	Maximum M12 Axial	1	D	M12	6121.2	552.2	5.2	34.4
LC 14-1	Maximum M12 Axial	1	D	M12	7930.4	775.6	4.0	24.5
LC 14-2	Maximum M12 Axial	1	D	M12	7867.9	775.5	4.0	24.5

Load case LC 14-1 and 2 have the highest axial load and are ok

Case Number	Description	Joint	Bolt	Bolt Type	Axial Force (N)	Shear Force (N)	Available Axial to Calculated	Available Shear to Calculated
LC 13-1	Maximum M10 Axial	12	A	M10	4393.3	5.5	5.0	2396.0
LC 13-2	Maximum M10 Axial	12	A	M10	2858.8	8.3	7.7	1585.8
LC 14-1	Maximum M10 Axial	12	A	M10	6516.0	9.0	3.4	1471.0
LC 14-2	Maximum M10 Axial	12	A	M10	5274.2	16.2	4.2	812.9

Load case LC 14-1 has the highest axial load and is ok

Note: Maximum shear force for of all cases and joints is less than 30% of available, Therefore it is not necessary to consider combined loading. (See User Note in Section J3.7)

Weld Results for APA under Thermal load

Case	Weld Location (by Joint Number)	Available Strength to Calculated
LC 13-1	1	5.1
LC 13-2	1	5.2
LC 14-1	1	4.1
LC 14-2	1	4.1

Load Case LC14--1 and -2 have the highest weld load and are ok.

Wire Tension Results for APA under Thermal load

Wire Tension Template will be modified for thermal cases to account for wire temperature. For load cases 14-1 and 14-2, it is assumed that the APA wires cool quickly and experience 50% extra preload. This will result in the wires tension being approximately 9.75N. Therefore the safety margin will be approximately 2.0

Note: All static transport cases were done using ASD and should have been done using LFRD. This will be corrected and will increase available stress and safety margins.

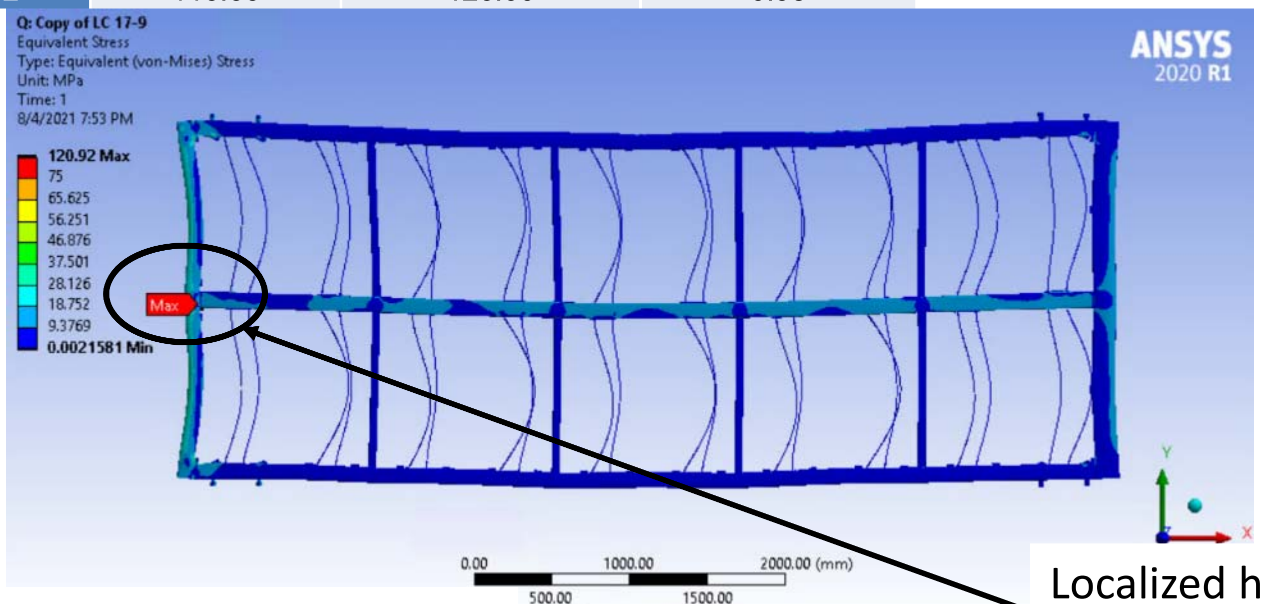
Frame Stresses for Static Transport Cases

Results from FEA

See following page for cases checked with Analytical method

Case	Maximum von Mises Stress (MPa)	Available Stress (MPa)	Utilization Ratio
LC 17-9	120.92	126.00	0.96
LC 17-10	110.89	126.00	0.88
LC 18-1	116.33	126.00	0.92
LC 18-2	119.81	126.00	0.95
LC 19-1	115.87	126.00	0.92
LC 19-2	116.66	126.00	0.93

LC 17-9 Highest peak stress for cases checked with FEA. UR < 1 is ok.



Stress plot for load case 17-9

Localized high stress at joint 17-9

Frame Stresses for “Static” Transport Cases

Results from analytical method - 360-16 AISC Chapter K HSS-to-HSS truss connection

Load case number	Axial Force [kN]	Bending Moment y [N-m]	Bending Moment z [N-m]	ASD - UR
LC 15	10.9	0.29	207	0.17
LC 16	10.9	0.25	168	0.15
LC 17-1	10.9	0.3	271	0.19
LC 17-2	10.88	0.3	262.9	0.19
LC 17-3	10.84	0.3	252	0.18
LC 17-4	10.8	0.3	232	0.175
LC 17-5	10.77	0.3	205.7	0.16
LC 17-6	10.74	0.2	172.9	0.15
LC 17-7	10.72	0.2	135.5	0.13
LC 17-8	10.71	0.1	94	0.12
LC 20-1	11.2	0.24	126.5	0.13
LC 20-2	10.9	-46.1	125.9	0.15

Highest Utilization Ratio (UR)

Bolt results for Static Transport Cases

M12 bolts with Maximum Axial force for each case

Case Number	Description	Joint	Bolt	Bolt Type	Axial Force (N)	Shear Force (N)	Available Axial to Calculated	Available Shear to Calculated
LC 15	Maximum M12 Axial	17	A	M12	4100	573	5.1	22.1
LC 16	Maximum M12 Axial	17	A	M12	3900	568	5.5	22.3
LC 17-1	Maximum M12 Axial	17	A	M12	4500	557	4.7	22.7
LC 17-2	Maximum M12 Axial	17	A	M12	4500	582	4.7	21.8
LC 17-3	Maximum M12 Axial	17	A	M12	4600	609	4.6	20.8
LC 17-4	Maximum M12 Axial	17	A	M12	4600	634	4.6	20.0
LC 17-5	Maximum M12 Axial	17	A	M12	4500	657	4.7	19.3
LC 17-6	Maximum M12 Axial	17	A	M12	4400	684	4.8	18.5
LC 17-7	Maximum M12 Axial	17	A	M12	4300	704	4.9	18.0
LC 17-8	Maximum M12 Axial	17	A	M12	4200	726	5.1	17.5
LC 17-9	Maximum M12 Axial	17	A	M12	4000	740	5.3	17.1
LC 17-10	Maximum M12 Axial	17	A	M12	3800	749	5.6	16.9
LC 18-1	Maximum M12 Axial	17	A	M12	2800	539	7.5	23.5
LC 18-2	Maximum M12 Axial	17	A	M12	2200	433	9.6	29.2
LC 19-1	Maximum M12 Axial	17	A	M12	2800	482	7.5	26.3
LC 19-2	Maximum M12 Axial	1	B	M12	2800	541	7.5	23.4
LC 20-1	Maximum M12 Axial	17	A	M12	3200	494	6.6	25.7
LC 20-2	Maximum M12 Axial	17	C	M12	3700	676	5.8	18.7

Load case 17-3 and 4 have the highest axial load and are ok

Note: Maximum shear force for of all cases and joints is less than 30% of available, Therefore it is not necessary to consider combined loading. (See User Note in Section J3.7)

Bolt results for Static Transport Cases

M10 bolts with Maximum Axial force for each case

Case Number	Description	Joint	Bolt	Bolt Type	Axial Force (N)	Shear Force (N)	Available Axial to Calculated	Available Shear to Calculated
LC 15	Maximum M10 Axial	12	A	M10	4200	17	3.5	526.5
LC 16	Maximum M10 Axial	12	A	M10	4000	14	3.7	617.0
LC 17-1	Maximum M10 Axial	12	A	M10	4600	47	3.2	188.5
LC 17-2	Maximum M10 Axial	12	A	M10	4500	48	3.2	184.1
LC 17-3	Maximum M10 Axial	12	A	M10	4500	44	3.3	202.3
LC 17-4	Maximum M10 Axial	12	A	M10	4400	38	3.3	230.0
LC 17-5	Maximum M10 Axial	12	A	M10	4200	32	3.5	271.4
LC 17-6	Maximum M10 Axial	12	A	M10	4000	25	3.6	348.8
LC 17-7	Maximum M10 Axial	12	A	M10	3800	17	3.8	523.3
LC 17-8	Maximum M10 Axial	12	A	M10	3500	8	4.1	1108.3
LC 17-9	Maximum M10 Axial	12	A	M10	3300	1	4.5	7524.9
LC 17-10	Maximum M10 Axial	12	B	M10	3100	12	4.8	766.3
LC 18-1	Maximum M10 Axial	12	B	M10	2600	1	5.6	13585.3
LC 18-2	Maximum M10 Axial	12	B	M10	2400	0	6.2	57322.2
LC 19-1	Maximum M10 Axial	12	B	M10	2600	4	5.7	2390.8
LC 19-2	Maximum M10 Axial	12	B	M10	2600	0	5.7	50121.3
LC 20-1	Maximum M10 Axial	12	A	M10	3600	38	4.1	231.8
LC 20-2	Maximum M10 Axial	12	A	M10	4600	70	3.2	125.5

Load cases 17-1,4 LC have the highest axial load and are ok

Note: Maximum shear force for of all cases and joints is less than 30% of available, Therefore it is not necessary to consider combined loading. (See User Note in Section J3.7)

Weld results for Static Transport Cases

Case	Weld Location (by Joint Number)	Available Strength to Calculated
LC 15	22	5.2
LC 16	17	5.6
LC 17-1	22	4.6
LC 17-2	17	4.7
LC 17-3	17	4.6
LC 17-4	17	4.6
LC 17-5	17	4.7
LC 17-6	17	4.8
LC 17-7	17	5.0
LC 17-8	17	5.2
LC 17-9	17	5.4
LC 17-10	17	5.8
LC 18-1	6	5.9
LC 18-2	6	4.7
LC 19-1	6	5.8
LC 19-2	6	5.9
LC 20-1	22	5.3
LC 20-2	17	6.0

Load Cases 17-1, -2, and -4 have the highest weld load and are ok.

Wire Tension results for Static Transport Cases

Case	Max 0° (N)	Max -36° (N)	Max +36° (N)	Minimum Safety Margin
LC 15	6.48	6.95	6.97	2.79
LC 16	6.48	6.91	6.93	2.80
LC 17-1	6.48	7.02	7.01	2.77
LC 17-2	6.48	7.00	7.00	2.77
LC 17-3	6.48	6.97	6.98	2.78
LC 17-4	6.48	6.93	6.94	2.80
LC 17-5	6.48	6.87	6.88	2.82
LC 17-6	6.48	6.81	6.80	2.85
LC 17-7	6.48	6.73	6.72	2.88
LC 17-8	6.48	6.65	6.63	2.92
LC 17-9	6.48	6.56	6.55	2.96
LC 17-10	6.47	6.52	6.53	2.97
LC 18-1	6.47	6.58	6.58	2.95
LC 18-2	6.47	6.61	6.61	2.93
LC 19-1	6.47	6.58	6.58	2.95
LC 19-2	6.47	6.58	6.59	2.95
LC 20-1	6.47	6.87	6.88	2.82
LC 20-2	6.44	6.85	6.87	2.82

LC 17-1 and -2 have the minimum safety margin and are ok

Note: Minimal safety margin is based on a design strength of 19.4N (actual minimum yield is 23.3N) divided by Maximum tension.

Frame Stresses for Dynamic Transport Cases

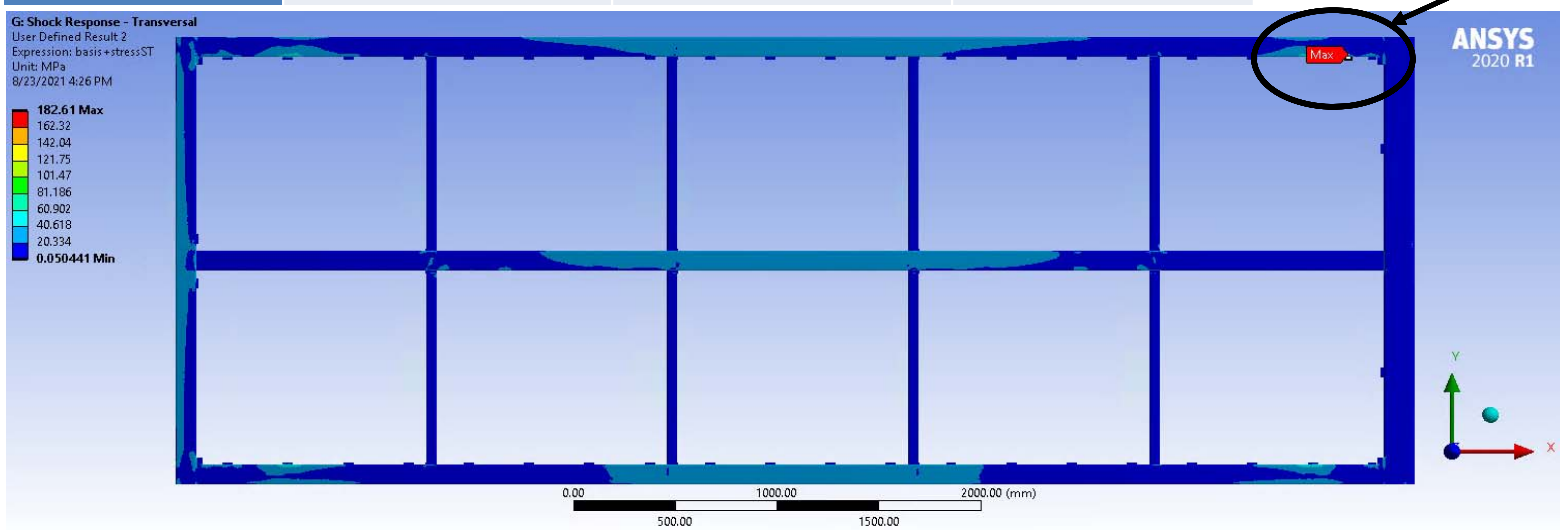
Results from FEA

See following page for cases checked with Analytical method

Case	Maximum Stress (MPa)	Available Stress (MPa)	Utilization Ratio
LCD 1-1	159.25	189.0	0.84
LCD 1-2	167	189.0	0.88
LCD 1-3	180.3	189.0	0.95
LCD 2-1	149.4	189.0	0.79
LCD 2-2	148.4	189.0	0.79
LCD 2-3	148.4	189.0	0.79
LCD 3-2	182.6	189.0	0.97
LCD 3-3	151.9	189.0	0.80

LCD 3-2 Highest peak stress for cases checked with FEA. UR < 1 is ok.

Localized high stress



Stress plot for load case LCD 3-2

Frame Stresses for Dynamic Transport Cases

Results from analytical method - 360-16 AISC Chapter K HSS-to-HSS truss connection

Load case number	Axial Force [kN]	Bending Moment y [N-m]	Bending Moment z [N-m]	LFRD - UR
LCD 3-1	11	0.5	483.8	0.19

Utilization Ratio (UR) is less than 1.

Bolt Results for Dynamic Transport Cases

M12 bolts with Maximum Axial force for each case.

Case Number	Description	Joint	Bolt	Bolt Type	Axial Force (N)	Shear Force (N)	Available Axial to Calculated	Available Shear to Calculated
LCD 1-1	Maximum M12 Axial	17	A	M12	3711.3	545.5	8.6	34.8
LCD 1-2	Maximum M12 Axial	17	C	M12	4303.6	1326.0	7.4	14.3
LCD 1-3	Maximum M12 Axial	17	C	M12	5063.8	829.8	6.3	22.9
LCD 2-1	Maximum M12 Axial	17	A	M12	5397.7	802.1	5.9	23.7
LCD 2-2	Maximum M12 Axial	17	C	M12	5403.8	811.1	5.9	23.4
LCD 2-3	Maximum M12 Axial	17	C	M12	5403.8	811.1	5.9	23.4
LCD 3-1	Maximum M12 Axial	17	C	M12	4457.3	613.1	7.1	31.0
LCD 3-2	Maximum M12 Axial	17	C	M12	3904.8	782.6	8.1	24.3
LCD 3-3	Maximum M12 Axial	17	C	M12	4463.7	716.7	7.1	26.5

Load cases LCD 2-2, and -3 have the highest axial load and are ok

Note: Maximum shear force for of all cases and joints is less than 30% of available, Therefore it is not necessary to consider combined loading. (See User Note in Section J3.7)

Bolt Results for Dynamic Transport Cases

M10 bolts with Maximum Axial force for each case

Case Number	Description	Joint	Bolt	Bolt Type	Axial Force (N)	Shear Force (N)	Available Axial to Calculated	Available Shear to Calculated
LCD 1-1	Maximum M10 Axial	12	A	M10	3670.8	86.5	6.0	152.5
LCD 1-2	Maximum M10 Axial	12	A	M10	5638.4	970.9	3.9	13.6
LCD 1-3	Maximum M10 Axial	5	A	M10	3789.9	16.7	5.8	792.1
LCD 2-1	Maximum M10 Axial	12	A	M10	6178.7	112.9	3.6	116.9
LCD 2-2	Maximum M10 Axial	12	A	M10	6137.0	110.1	3.6	119.8
LCD 2-3	Maximum M10 Axial	12	A	M10	6137.0	110.1	3.6	119.8
LCD 3-1	Maximum M10 Axial	5	A	M10	6332.3	79.2	3.5	166.7
LCD 3-2	Maximum M10 Axial	12	A	M10	5345.0	153.1	4.1	86.2
LCD 3-3	Maximum M10 Axial	12	A	M10	3658.6	74.2	6.0	177.8

Load case LCD 3-1 has the highest axial load and is ok

Note: Maximum shear force for of all cases and joints is less than 30% of available, Therefore it is not necessary to consider combined loading. (See User Note in Section J3.7)

Weld Results for Dynamic Transport Cases

Case	Weld Location (by Joint Number)	Available Strength to Calculated Load
LC 1-1	17	8.8
LC 1-2	M20 foot-high-far	4.4
LC 1-3	17	6.3
LC 2-1	17	6.0
LC 2-2	17	6.1
LC 2-3	17	6.1
LC 3-1	M20 head-low-far	7.0
LC 3-2	M20 foot-high-far	6.0
LC 3-3	17	7.2

Load Case LCD 1-2 has the highest weld load and is ok.

Wire Results for Dynamic Transport Cases

Case	Max 0° (N)	Max -36° (N)	Max +36° (N)	Maximum Available (N)	Minimum Safety Margin
LCD 1-1	6.48	7.38	7.22	19.40	2.63
LCD 1-2	6.47	6.84	6.90	19.40	2.81
LCD 1-3	6.47	6.78	6.80	19.40	2.85
LCD 2-1	6.47	6.87	6.88	19.40	2.82
LCD 2-2	6.50	8.74	8.83	19.40	2.20
LCD 2-3	6.47	6.87	6.88	19.40	2.82
LCD 3-1	6.47	7.07	7.02	19.40	2.74
LCD 3-2	6.48	6.85	6.92	19.40	2.80
LCD 3-3	6.48	6.87	6.94	19.40	2.79

LCD 2-2 has the minimum safety margin and is ok

Note: Minimal safety margin is based on a design strength of 19.4N (actual minimum yield is 23.3N) divided by Maximum tension.

Buckling

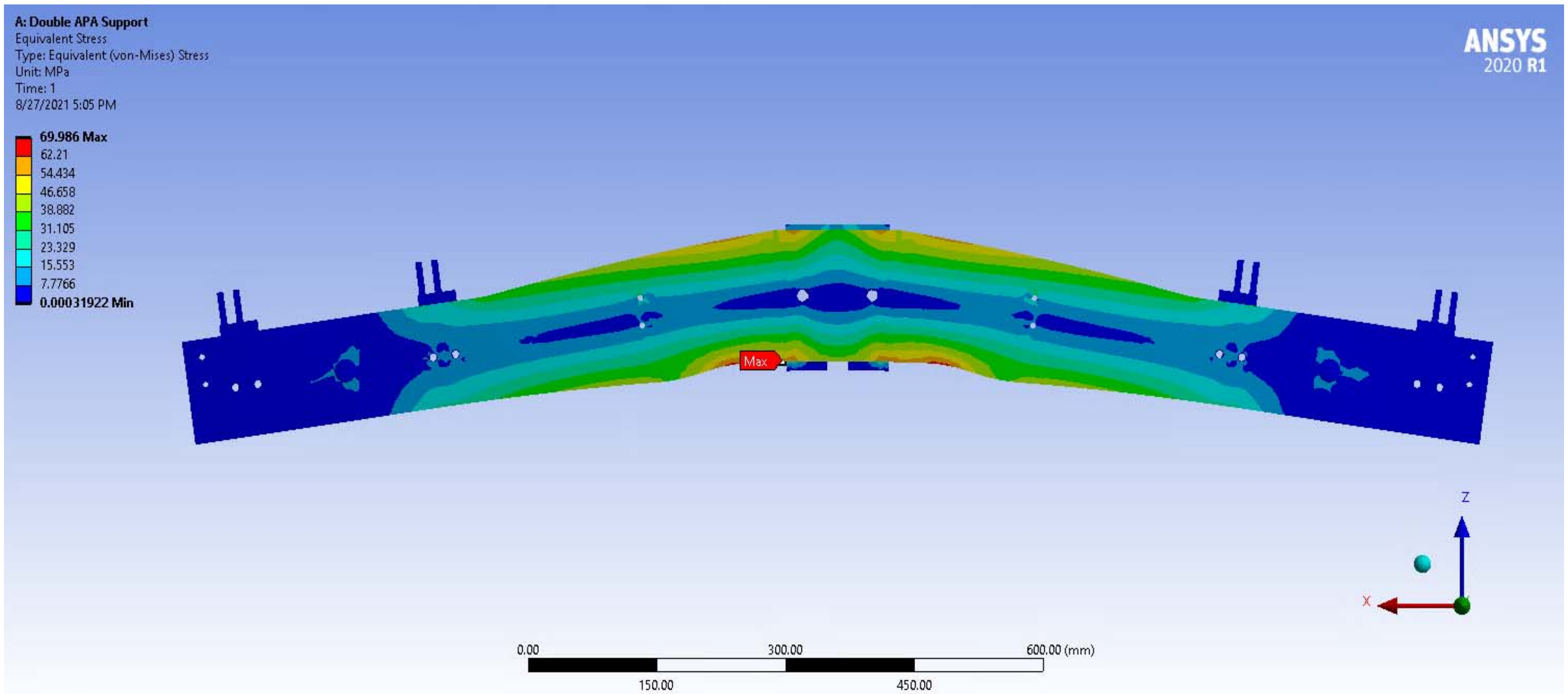
Design Guide 27 section 5.3 provides design guidance for the buckling verification method.

To assess the buckling of all the box beams:

- The available axial and flexural strength was calculated for all the structural members in the APA.
- The actual loads and moments for all connection joints and all load cases where assumed to be applied to the structural member with the lowest strength.
- All load cases show a UF smaller than 1 so all the box beams meet the buckling requirements.

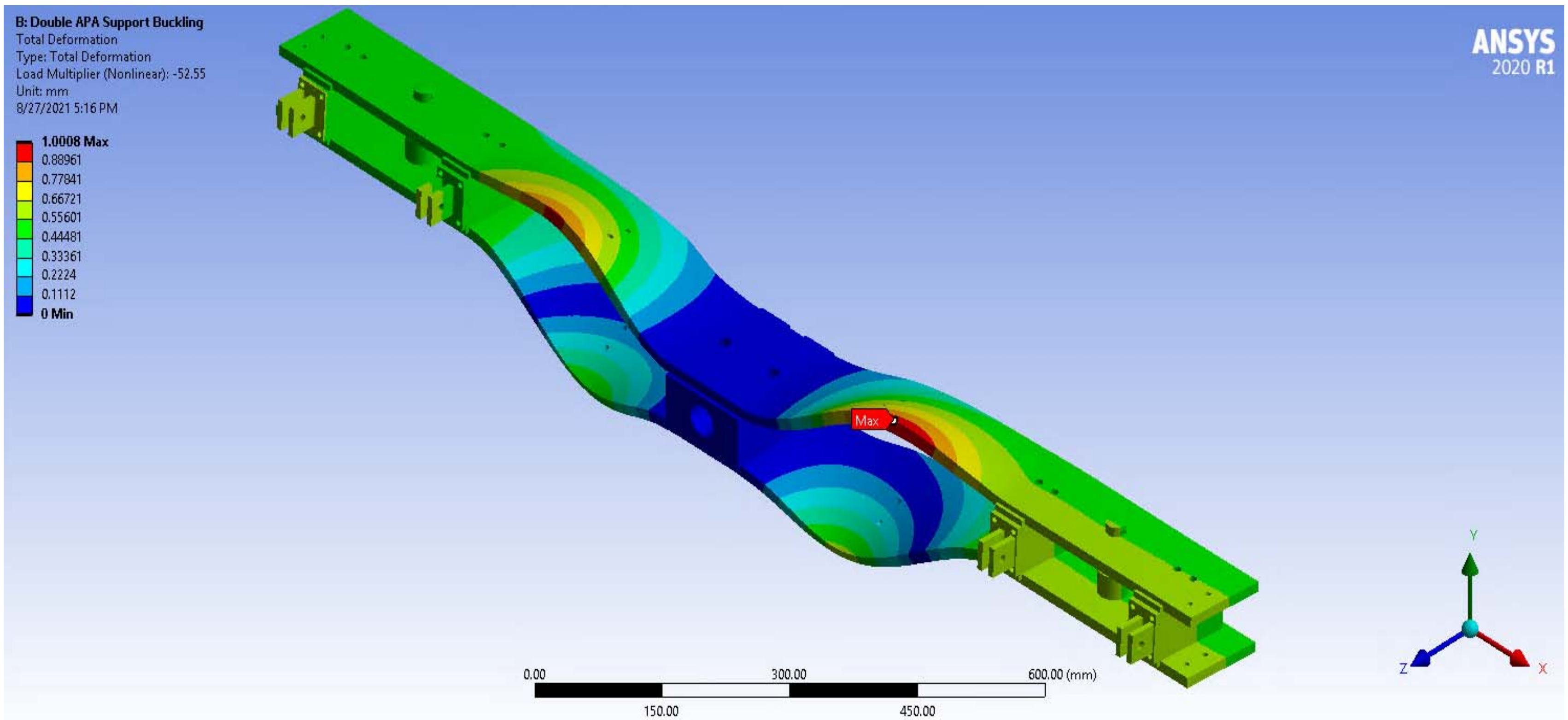
APA Yoke Stress – Installed case under gravity load

Peak yoke stress is approximately 70 MPa. Well below the available of **189 MPa.**



APA Yoke Stress – Installed case - Buckling

The yoke was analyzed for buckling under the loading in the installed case. The load factor of 52.55 is less than 10 and is acceptable.



APA 25mm pin – Installed case

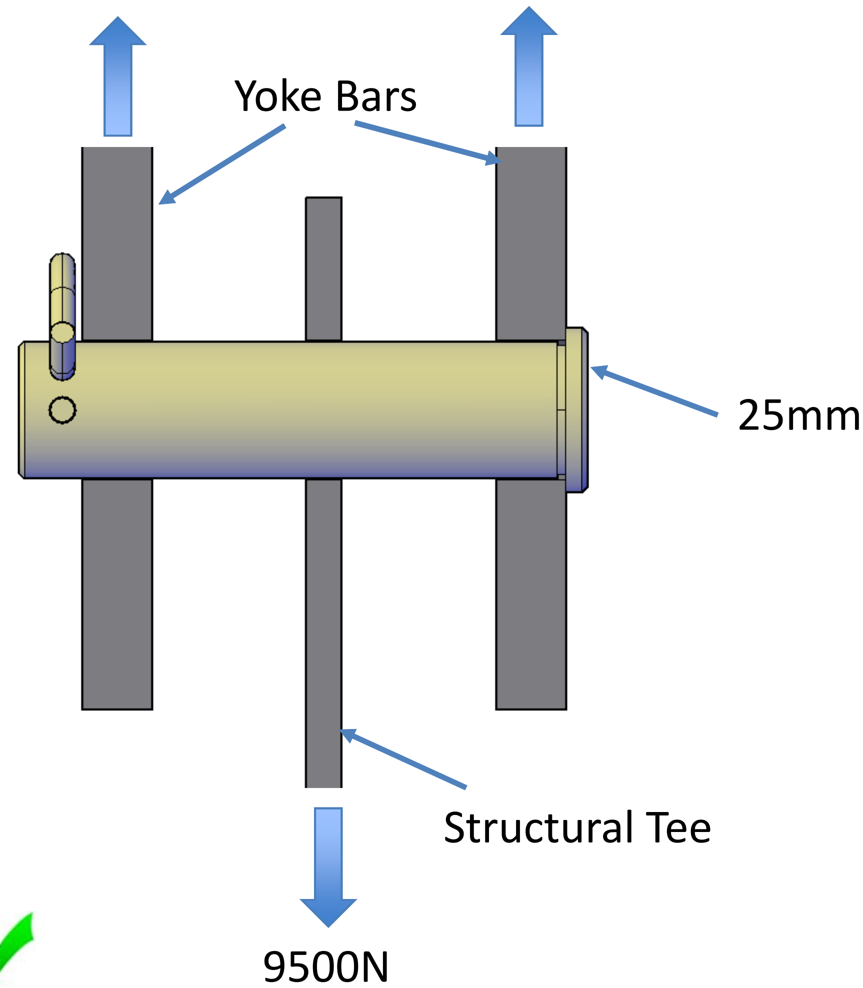
Based on the analysis method recommended by DESIGN GUIDE 27 and AISC, the combined bending and shear force factor shows the 25mm PIN to be safe.

Combined Bending and Shear Forces

$$\frac{M_{bending}}{M_{cy}} + \left(\frac{V_{ACTUAL}}{V_{cy}}\right)^2 = 0.89$$

AISC Eq.(H3-6)*
Value < or = to 1

*Equation adapted due to no axial or torsion load



Structural Tee Analysis – Installed case

Required Strength = 9,663N

Results for pinned connection

Tensile rupture on net section

Available = 61,920N

Tensile yielding on gross section

Available = 50,080N

Tensile yielding on net section

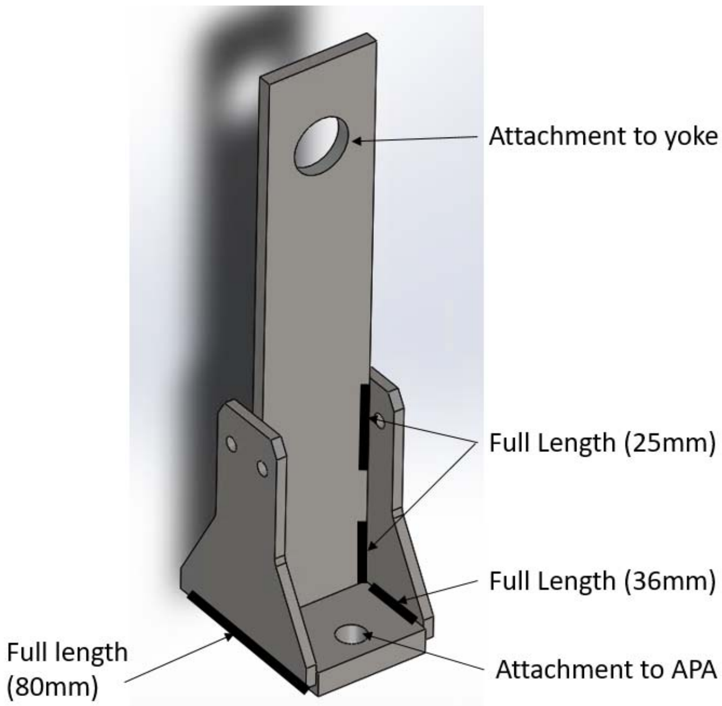
Available = 29,750N

Shear rupture on effective area

Available = 77,340N

Bearing stress between pin and hole

Available = 44,360N



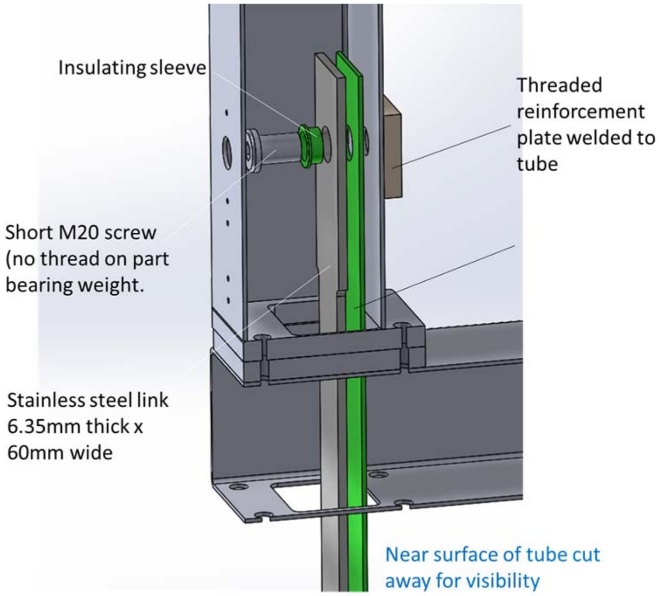
Welds

Available strength = 350N/mm

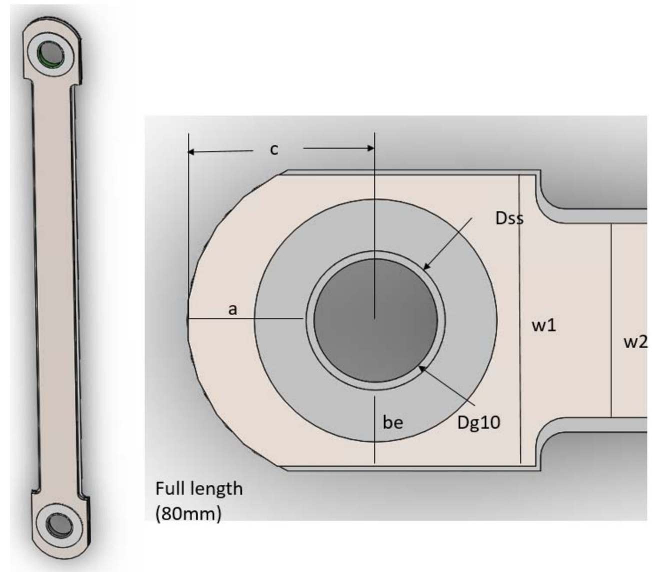
Unit load on vertical link to gusset welds = 49N/mm

Unit load on gussets to base plate welds = 32N/mm

APA to APA link– Installed case



APA to APA link hardware



Link end detail

APA to APA link– Installed case

Required Strength = 4,785N

Results for pinned connection

Tensile rupture on net section

Available = 40,790N

Tensile yielding on gross section

Available = 44,340N

Tensile yielding on net section

Available = 27,760N

Shear rupture on effective area

Available = 54,370N

Bearing stress between 28.7mm sleeve OD and 28.7mm hole

Available = 38,180N

Bearing stress of FR4 sleeve between 25.2mm pin and 25.4mm hole (ASD)

FS=262MPa/28.5MPa=9.2 (Required is 3.75)

APA to APA link– Thermal considerations

Evaluation of stresses in the link due to the foot tube in the bottom APA cooling faster than the foot tube in the top.

Temperature assumptions:
Thermal vertical gradient of GAr at 17K/m
Head end of the bottom APA in LAr and bottom APA foot tube at 88K (Very conservative)
Top APA foot tube at temperature Gar 9 m above the LAr = 241K
Difference in shrinkage between the top and bottom foot tube = 4.6mm (2.3mm per link)
Shrinkage is based on a temperature difference of 153K. Thermal gradient of GAr at the foot tubes is 2.3K. It is unlikely this temperature difference will be more than 10K.

Results:
Using equations for the flexure of guided beams, the moment on the end of the link is determined. This moment is used to calculate the resulting stress distribution across the contact area of the pin/sleeve interface.

Total stress = Bearing stress + bending stress = 28.5 + 33.8 = 62.3MPa

FS = 262MPa/62.3MPa = 4.2 (3.75 is required).

Work left to do:

- Revise the results for the Static Transport cases to use the LFRD rather than ASD method of checking strength. This will increase the safety margins.
- For the Dynamic Drop Case, the check of welds and bolts needs to be revised to use the LFRD method.
- Complete the check of wire tension for the thermal load cases.
- Complete the check of connections between the yoke and the APA frame for gravity and thermal loading.
- Complete the analysis of the APA link bolt.
- Provide written justification that all installation load cases are covered.
- Provide conclusions on the acceptability of the frame deformations for the various load cases.

Conclusion:

- Bolts and welds
  - For the analyses completed so far, the available/design strength of the joints exceed the required strength.
- Structural members
  - For the load cases completed so far, except for near joint 11, the available/design stress exceeds the elastic FEA calculated stresses. Near joint 11, available stresses sometimes are less than FEA stresses. However, due to stress concentrations (and singularities) it can be very conservative to compare available stresses to elastic FEA stresses. Joint 11 is ok when checked with the analytical method.

- The available strength of the yoke, the 25mm pin, and the structural tees exceed the required strength when subject to gravity load. The pins and structural tee connection will be checked under gravity and thermal load.

- The available strength of the link exceeds the required strength when subject to gravity loads and thermal strain between the upper and lower foot tubes.