APA Shipping frame Design

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LBNF/DUNE FDR: APA

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Outline

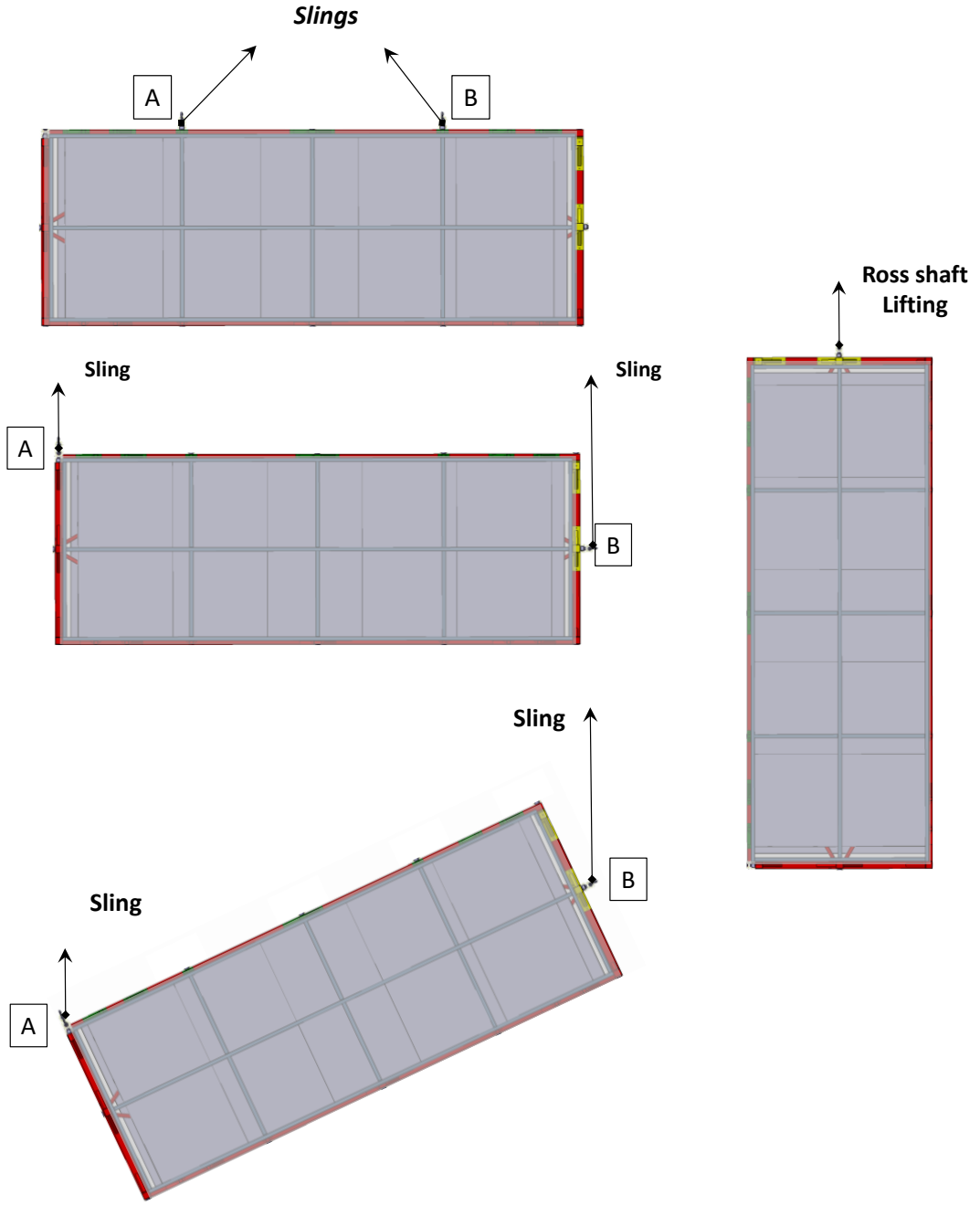
- Purpose
- Requirements
- Geometrical configuration
- Materials
- Loading situations
- Structural analysis
- Codes and regulations
- FEA results and verifications
- Final considerations

Documentation

- APA shipping frame memorandum: https://edms.cern.ch/document/2330505/2
- APA Shipping frame drawings: https://edms.cern.ch/document/2477326/1
- APA shipping frame analysis plan: https://edms.cern.ch/document/2509414/2
- Transportation analysis guidelines: https://edms.cern.ch/document/2366873/1
- **APA shipping frame engineering analysis**: https://edms.cern.ch/document/2607623/1
- AVMR shipping frame assembly analysis (Vibrostop): https://edms.cern.ch/document/2617816/1

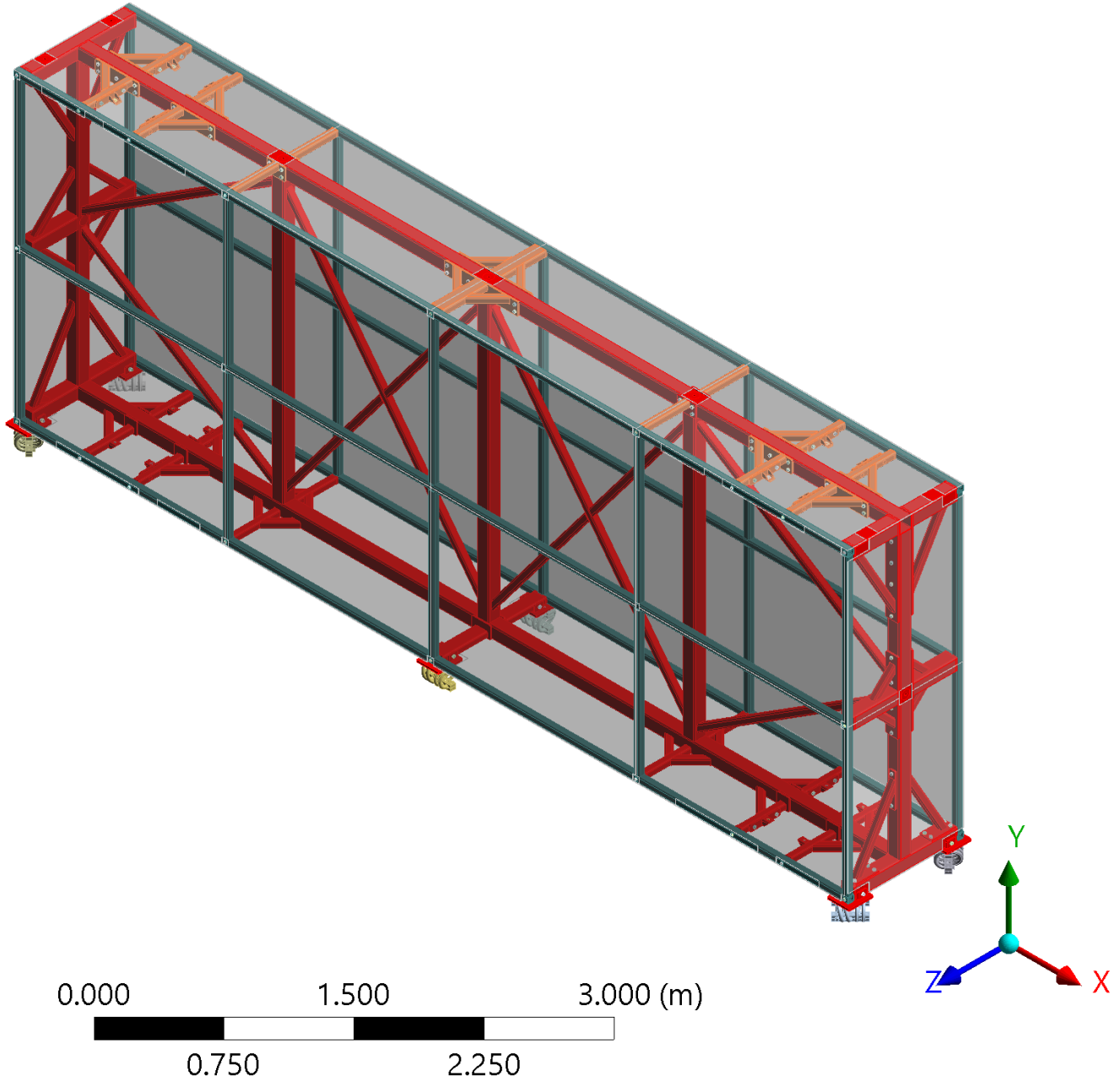
Purpose

- Lifting and Handling tool
- Transportation box
- Storage container



Geometrical configuration

- Central frame
- Closing and supporting top/end parts
- Lateral frame
- Protective sheeting
- Absorbers
- Lifting rings



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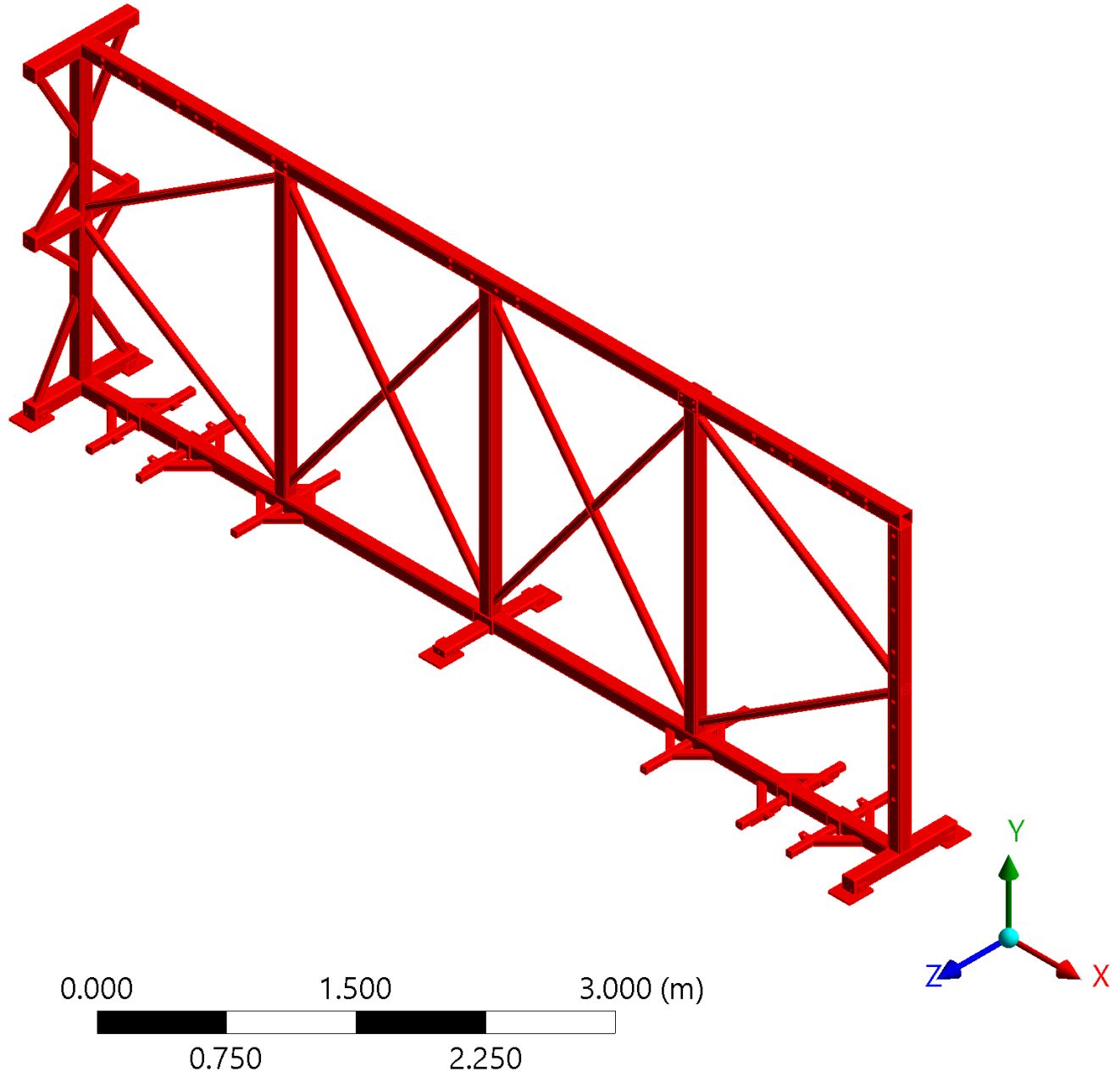

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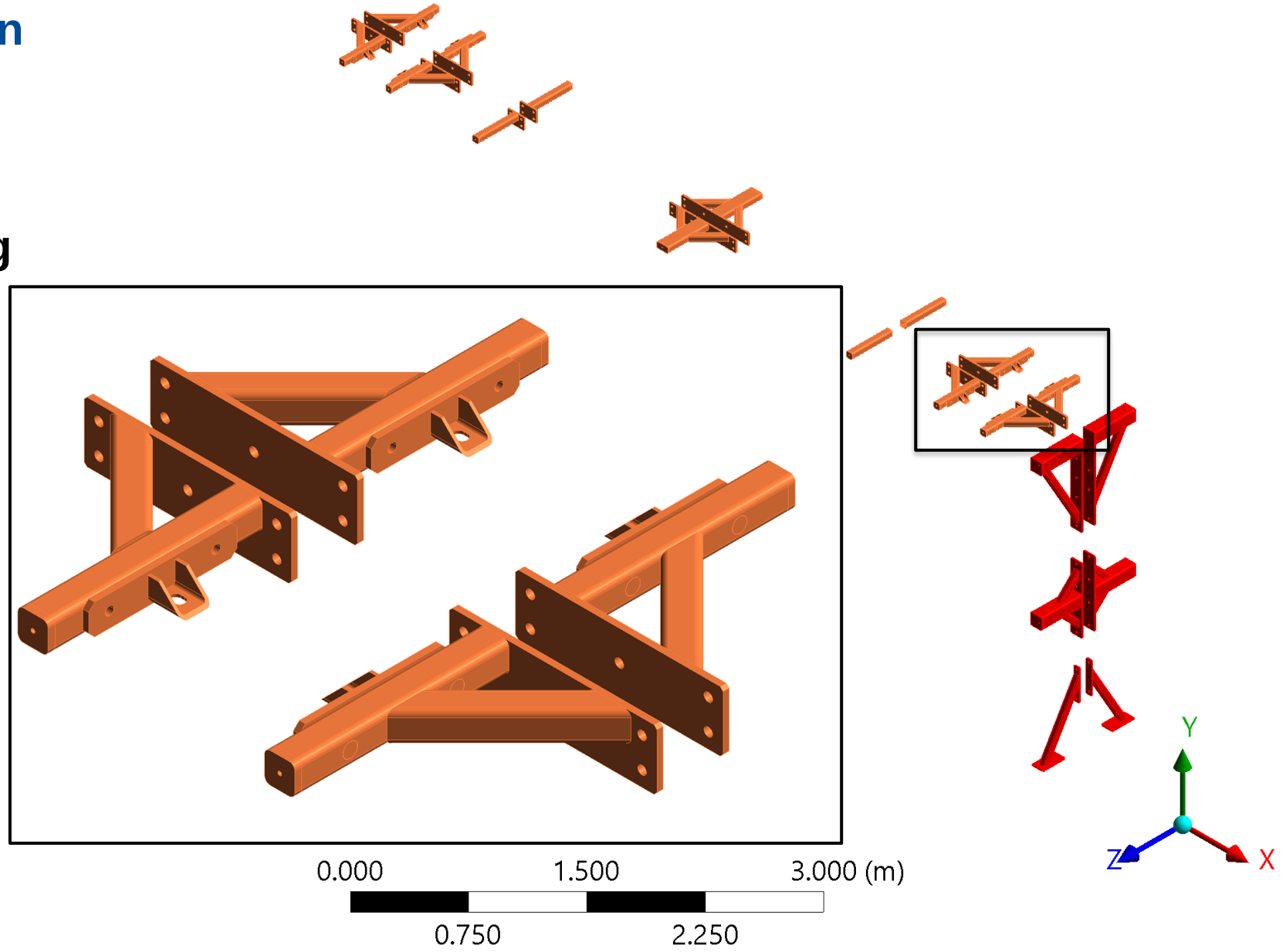

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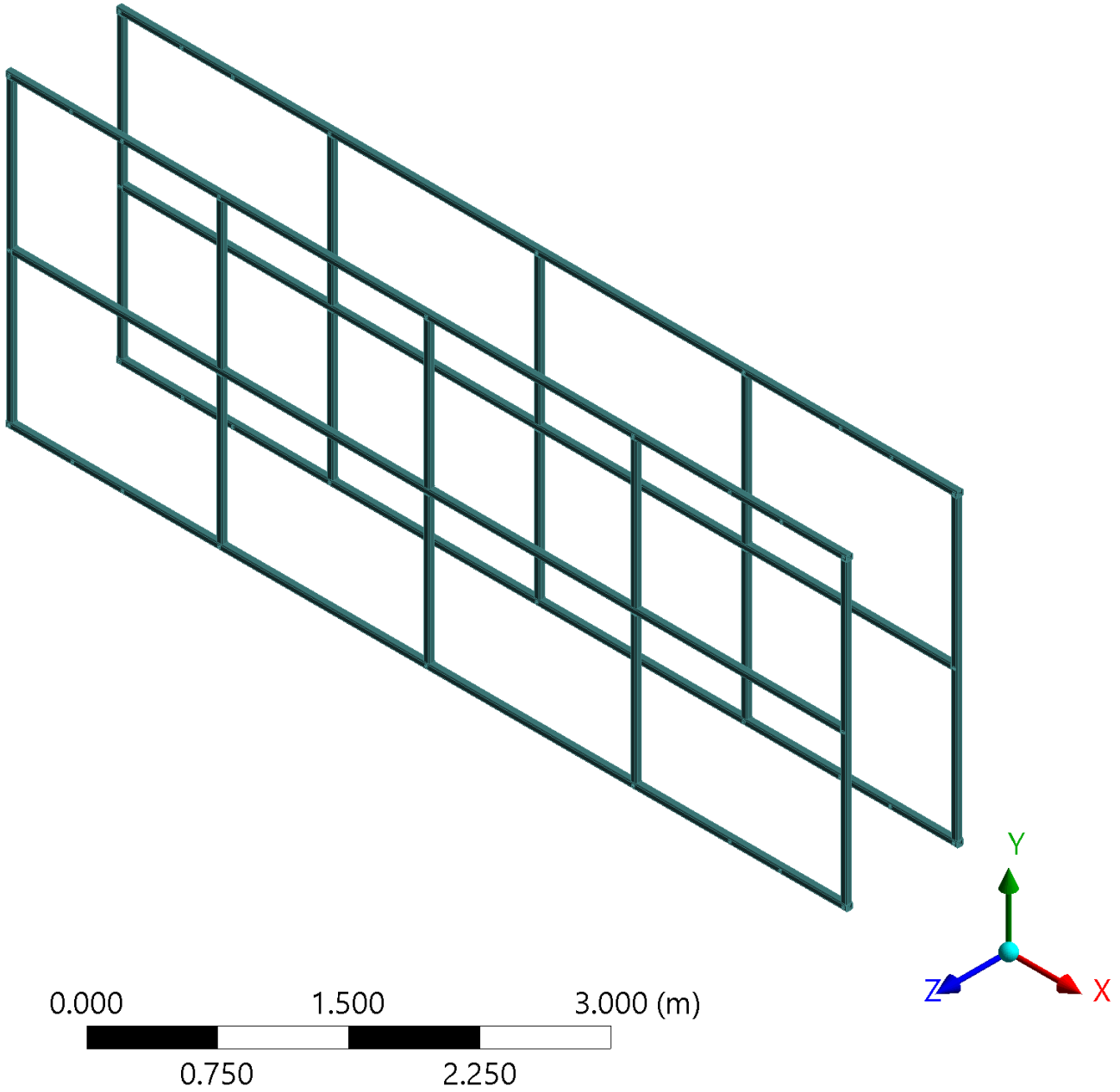

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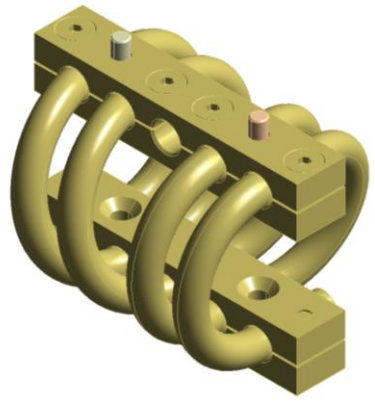
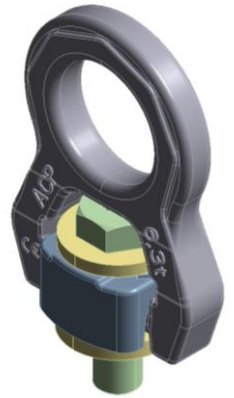
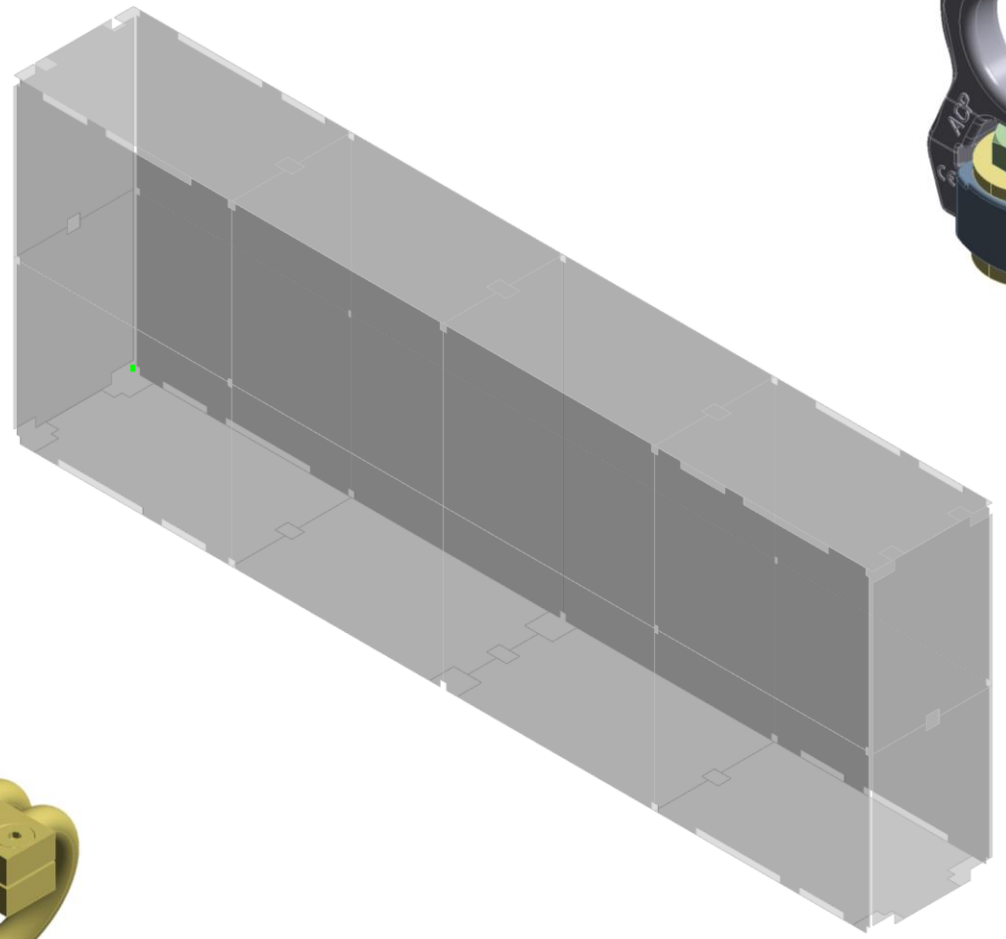
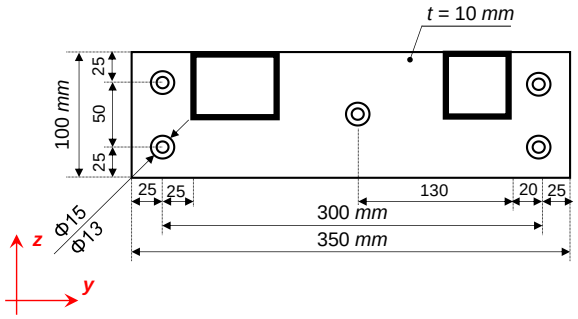




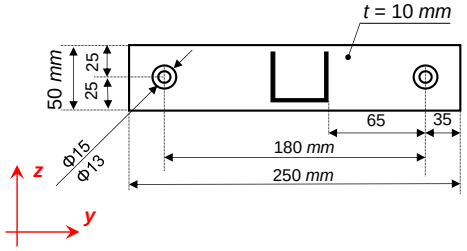


Geometrical configuration

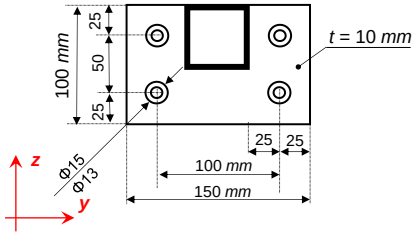
Connection 1



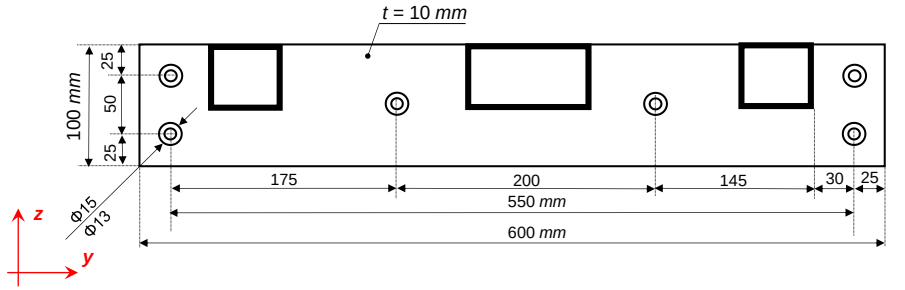
Connection 2

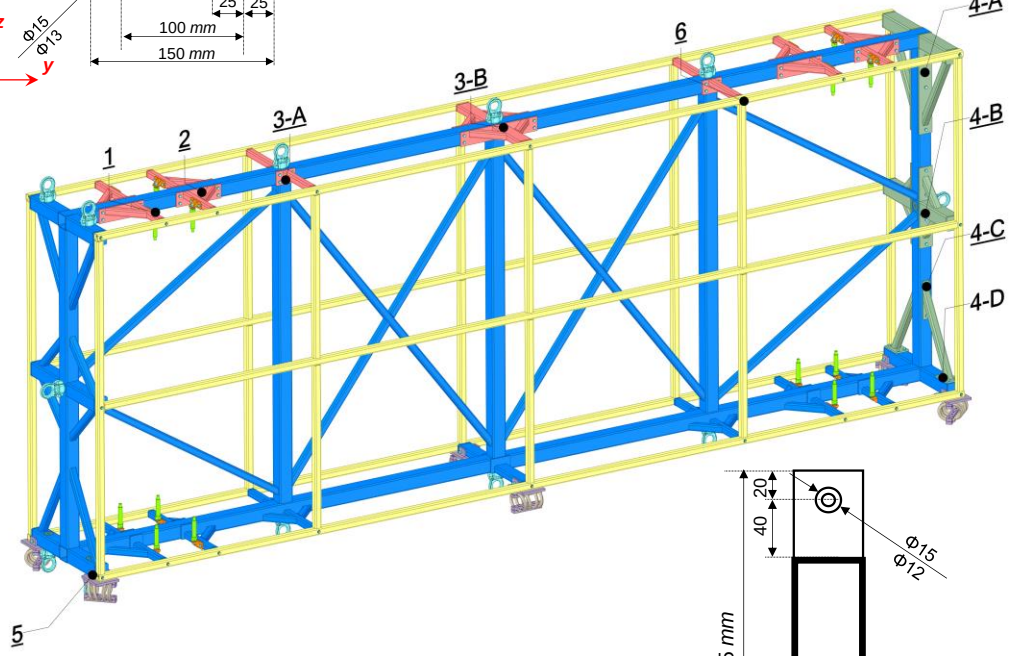


Connection 3A

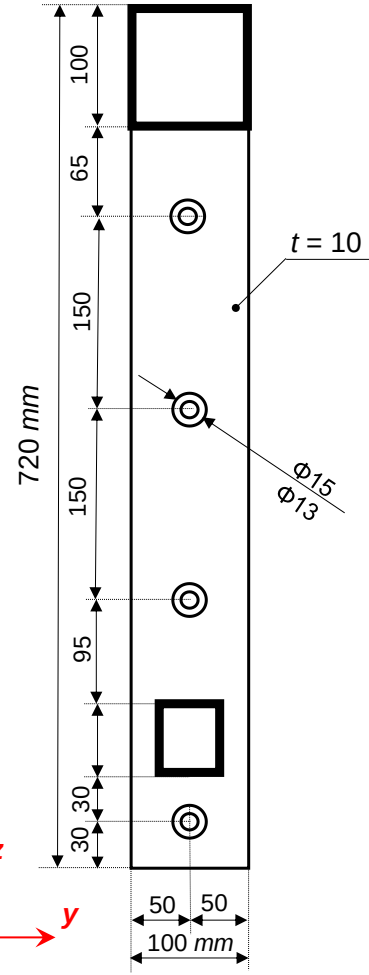


Connection 3B





Connection 4A



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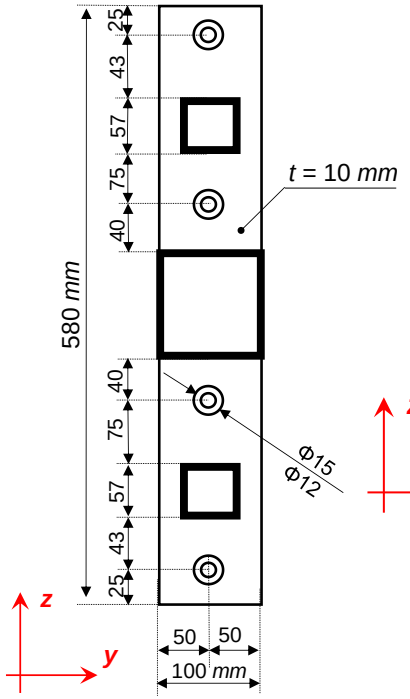
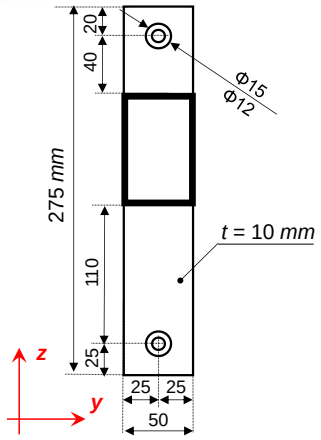
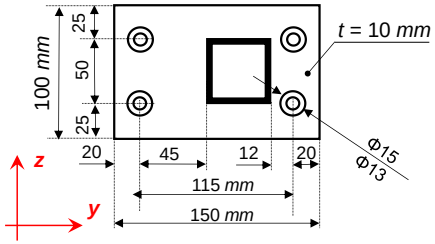


Connection 4C



Connection 4D



Materials and profiles

Rectangular hollow sections – S355

Bolts – gr.10.9

APA RHS – SS304L

Material	Density *[kg/m³]*	Poisson ratio *[-]*	Young Modulus *[GPa]*	Shear Modulus *[GPa]*	Mean CTE *[1/K]x10⁻⁶*	Yield strength *[MPa]*	Tensile strength *[MPa]*
S355	7850	0.3	210	81	12	355	510
Gr. 10.9						900	1000
SS 304L	7850	0.3	200	77	15	220	520

Loading situations

LIFTING AND QUASI-STATIC

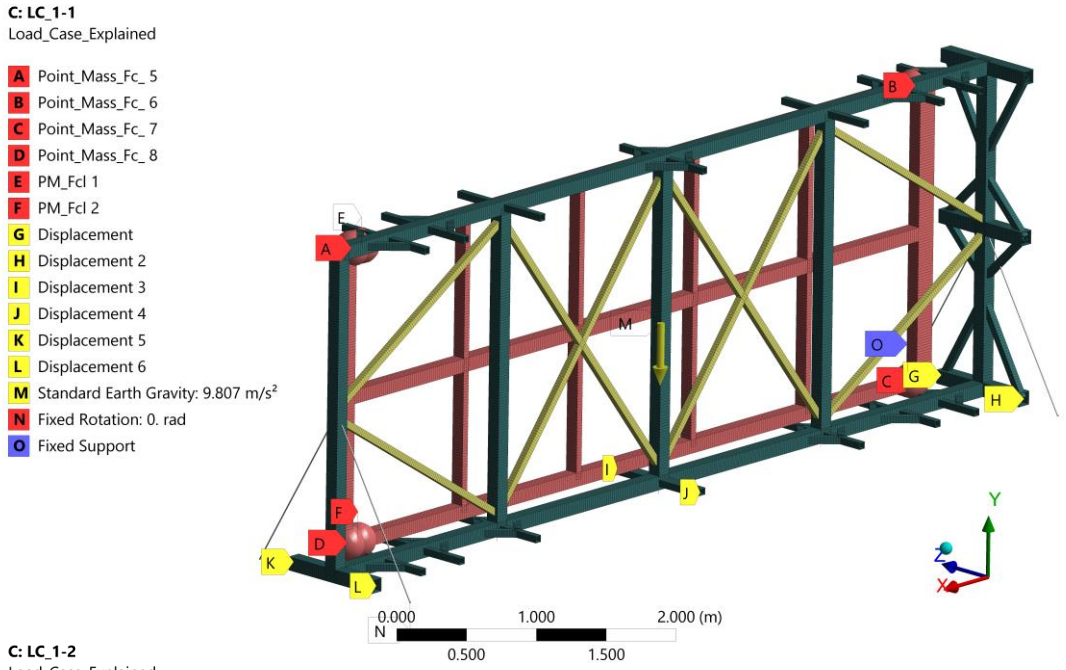
I. ***ASF supported on a cart, in landscape orientation.***

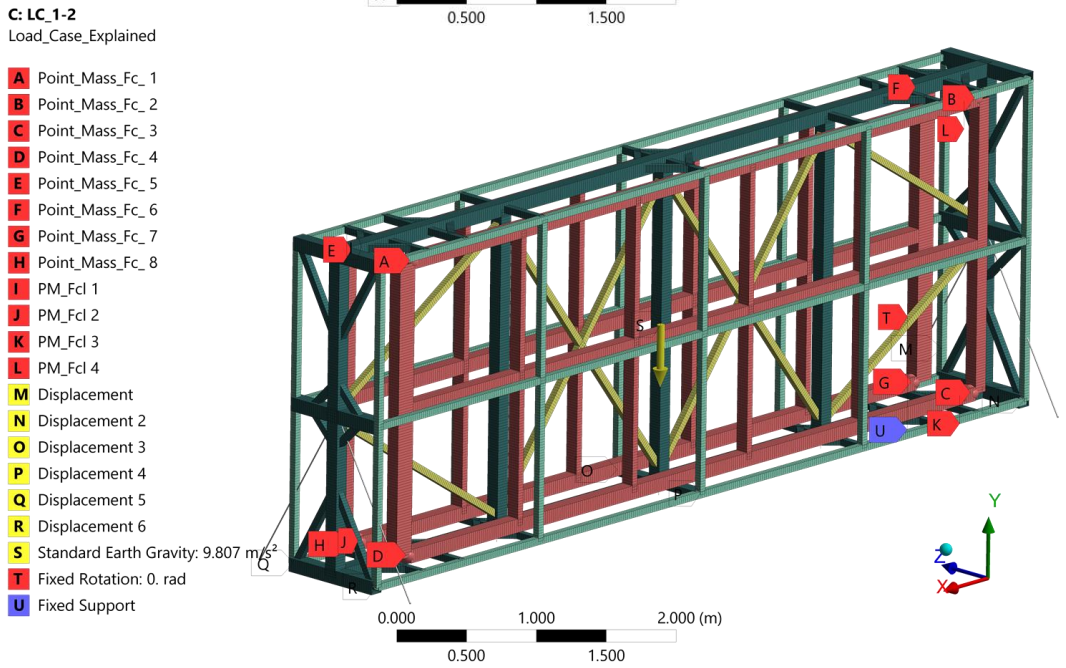
II. *ASF Lifting in landscape orientation from top central points.*

III. *ASF Lifting from landscape to vertical orientation, from end lifting points.*

IV. *ASF Ross shaft lowering.*

V. *ASF supported on a cart, in vertical orientation.*





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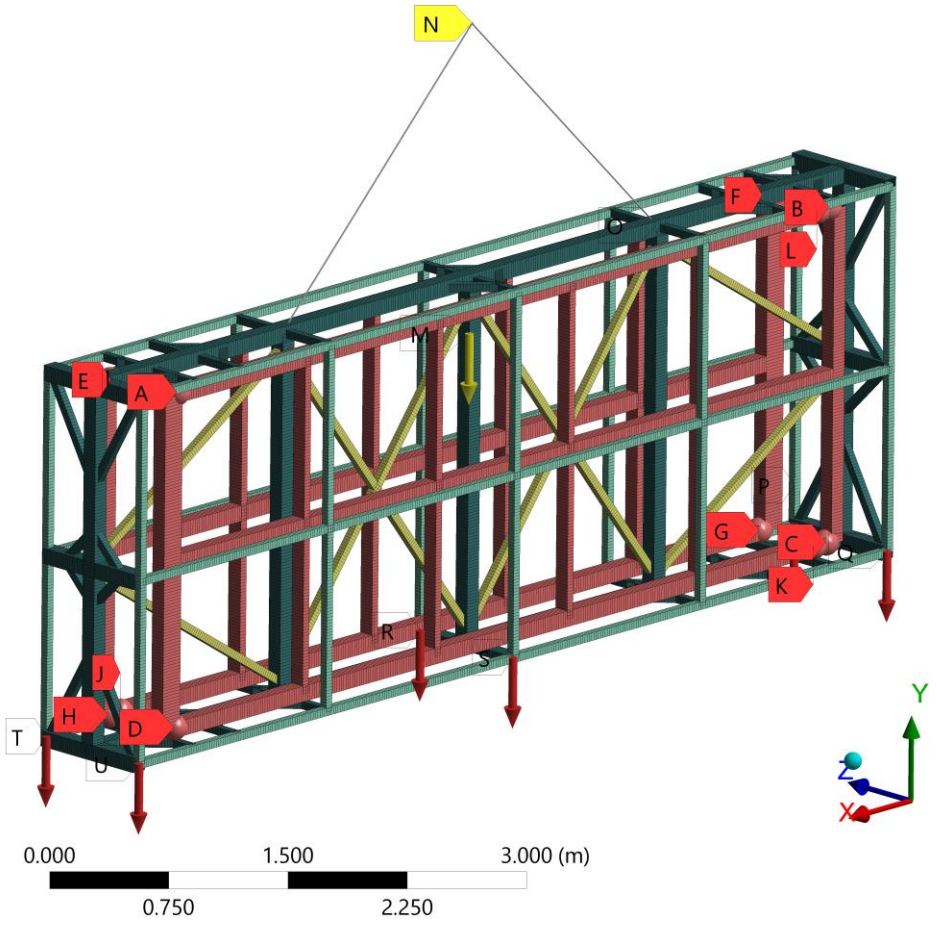
C: LC_2
Load_Case_Explained

- A Point_Mass_Fc_ 1
- B Point_Mass_Fc_ 2
- C Point_Mass_Fc_ 3
- D Point_Mass_Fc_ 4
- E Point_Mass_Fc_ 5
- F Point_Mass_Fc_ 6
- G Point_Mass_Fc_ 7
- H Point_Mass_Fc_ 8
- I PM_Fcl 1
- J PM_Fcl 2
- K PM_Fcl 3
- L PM_Fcl 4
- M Standard Earth Gravity: 9.807 m/s²
- N Remote Displacement
- O Displacement
- P Base_Frame_ 1: 1000 N
- Q Base_Frame_ 2: 1000 N
- R Base_Frame_ 3: 1000 N
- S Base_Frame_ 4: 1000 N
- T Base_Frame_ 5: 1000 N
- U Base_Frame_ 6: 1000 N



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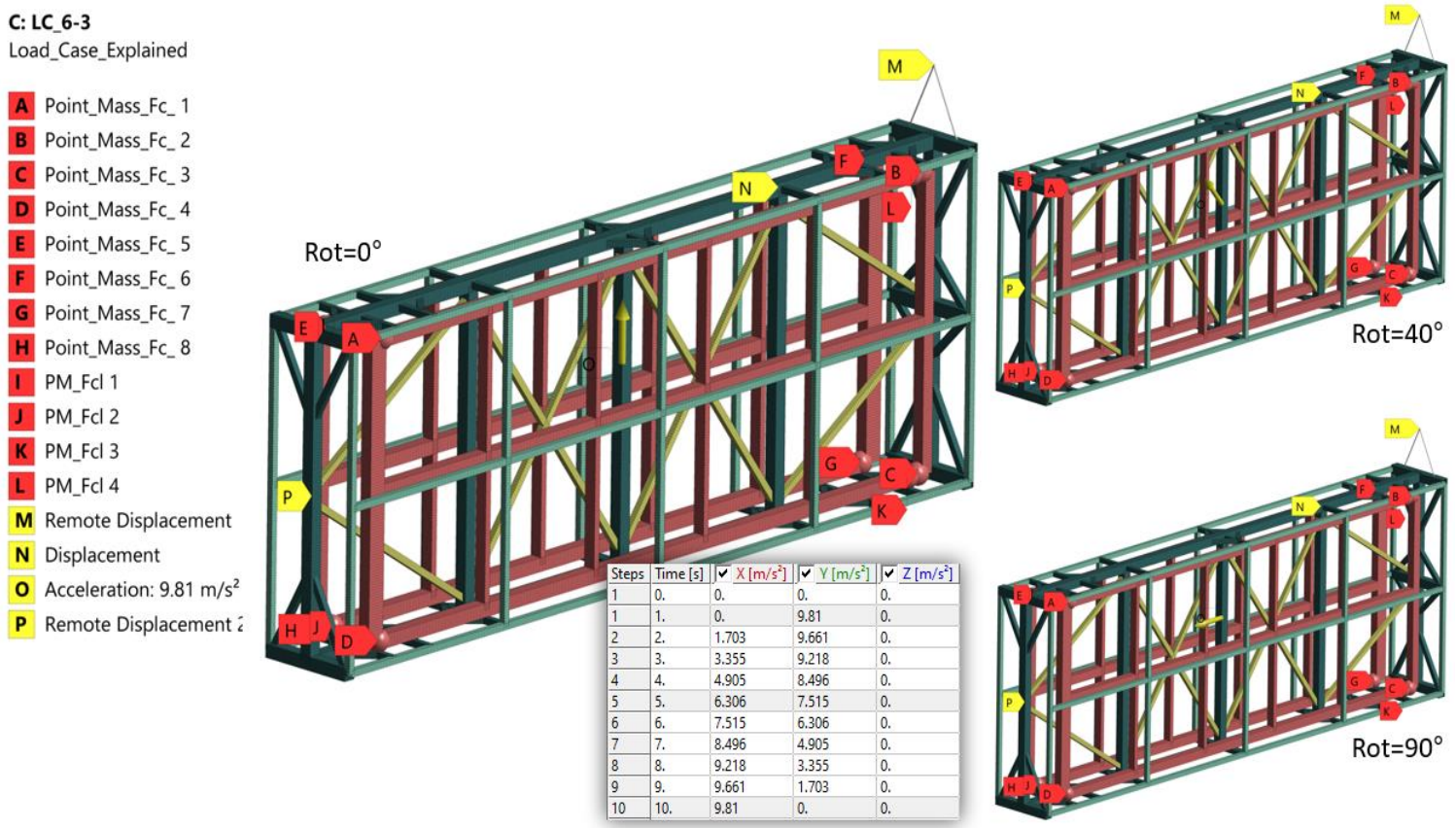

Steps	Time [s]	X [m/s²]	Y [m/s²]	Z [m/s²]
1	0.	0.	0.	0.
1	1.	0.	9.81	0.
2	2.	1.703	9.661	0.
3	3.	3.355	9.218	0.
4	4.	4.905	8.496	0.
5	5.	6.306	7.515	0.
6	6.	7.515	6.306	0.
7	7.	8.496	4.905	0.
8	8.	9.218	3.355	0.
9	9.	9.661	1.703	0.
10	10.	9.81	0.	0.

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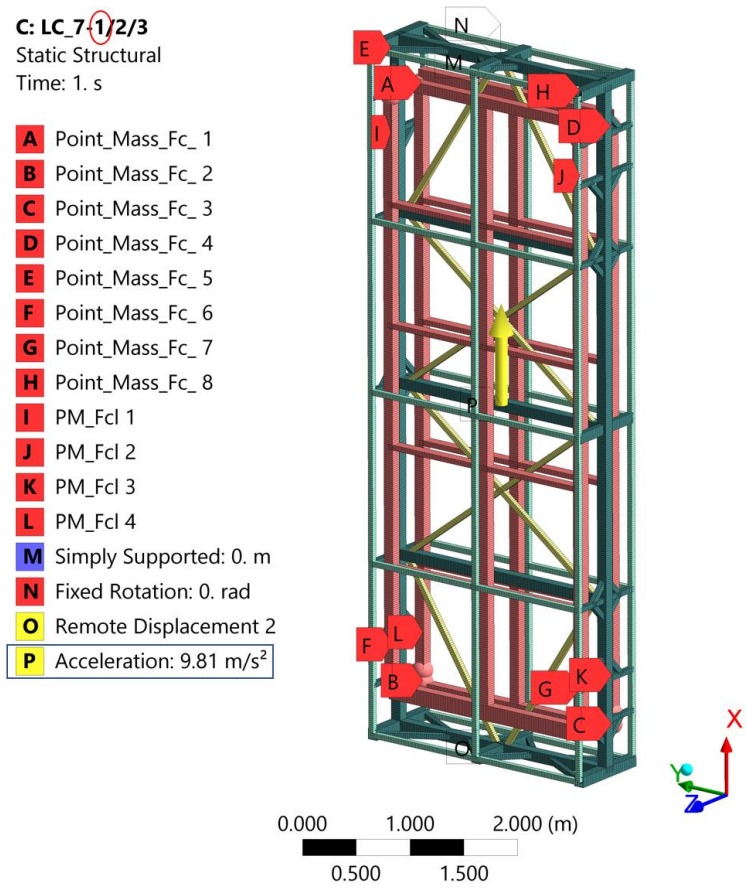

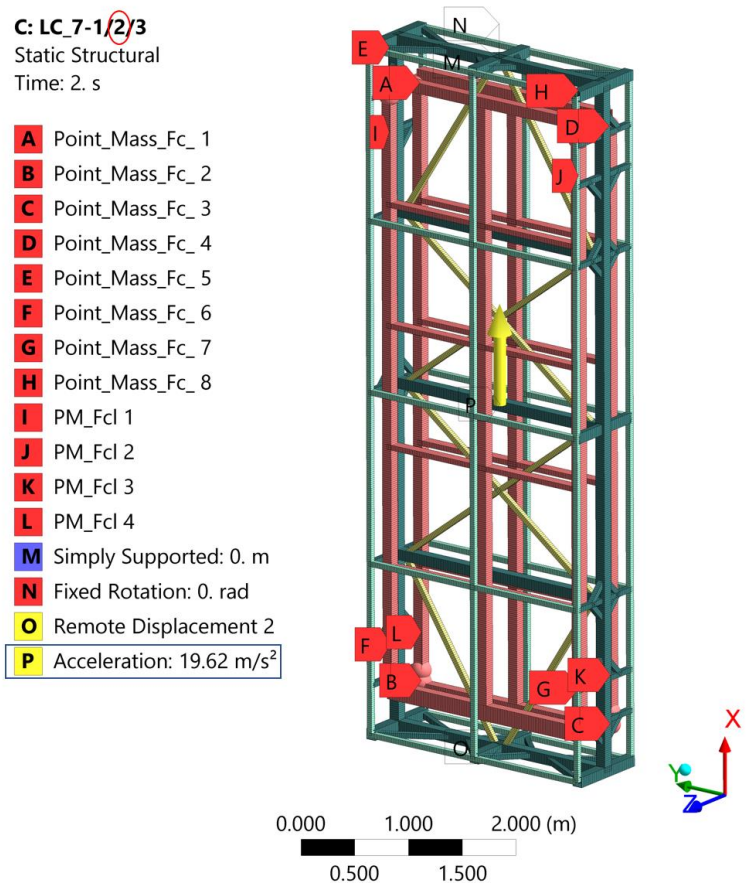

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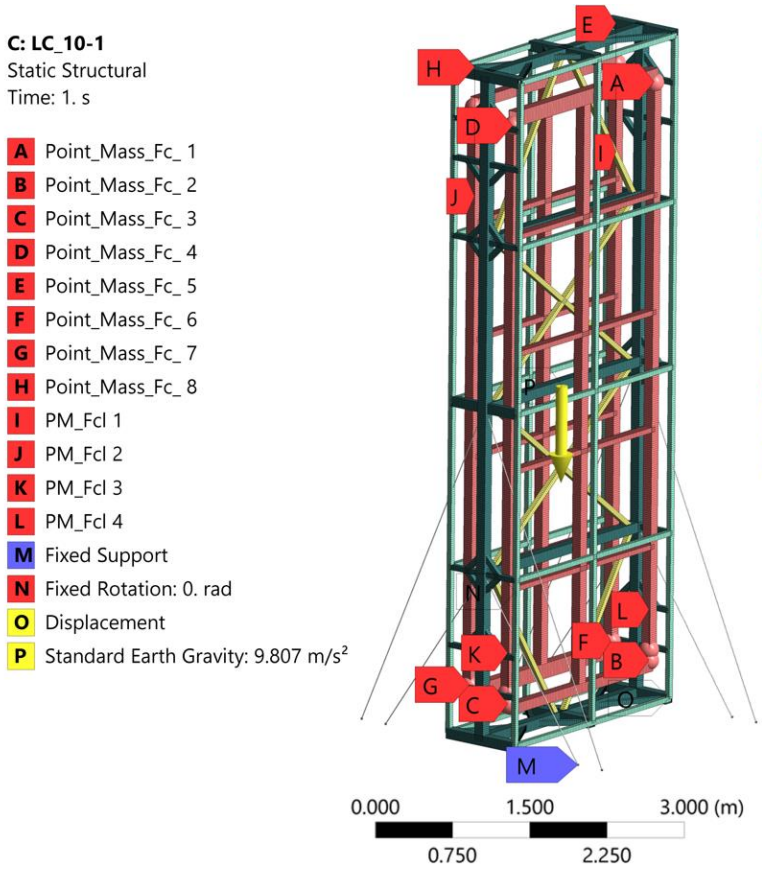
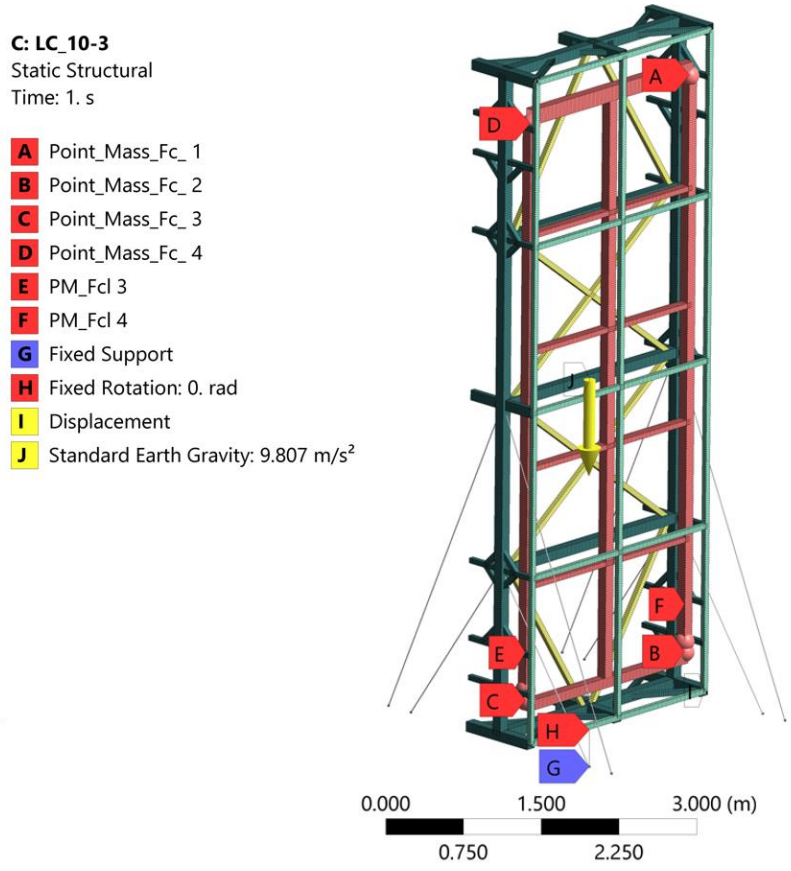




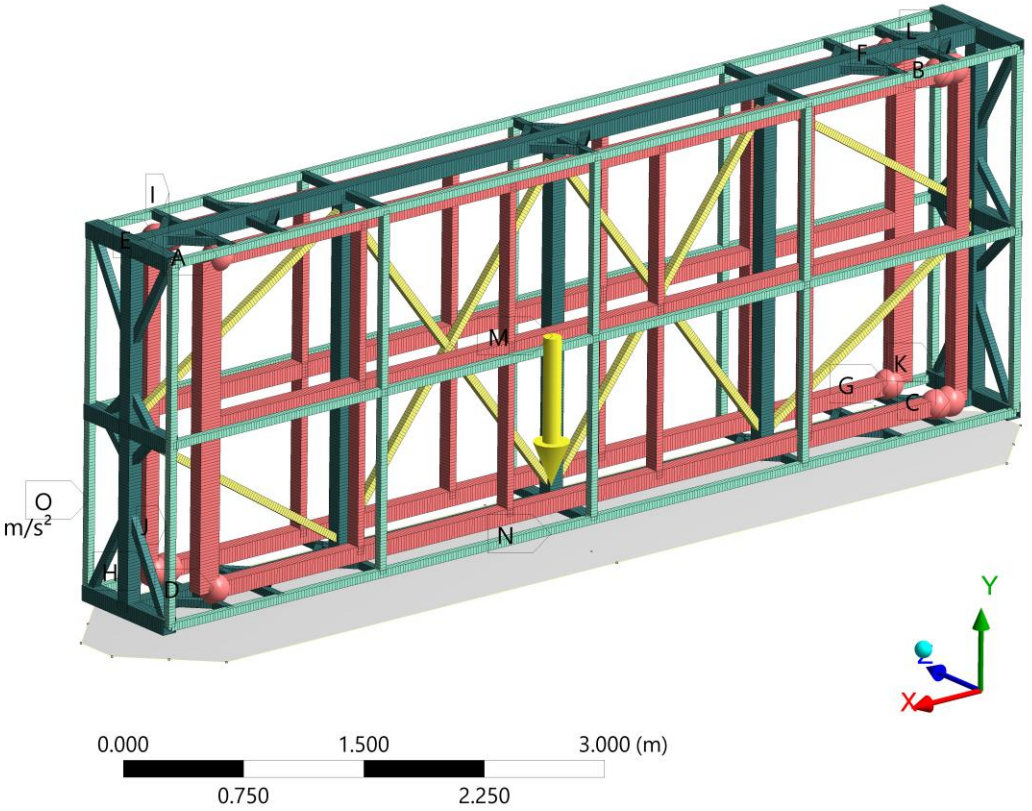
Loading situations

THERMAL

VI. ASF During Transportation – thermal analysis

C: LC_Thermal_+-20deg
Static Structural
Time: 2. s

- A Point_Mass_Fc_ 1
- B Point_Mass_Fc_ 2
- C Point_Mass_Fc_ 3
- D Point_Mass_Fc_ 4
- E Point_Mass_Fc_ 5
- F Point_Mass_Fc_ 6
- G Point_Mass_Fc_ 7
- H Point_Mass_Fc_ 8
- I PM_Fcl 1
- J PM_Fcl 2
- K PM_Fcl 3
- L PM_Fcl 4
- M Standard Earth Gravity: 9.807 m/s²
- N Remote Displacement
- O Thermal Condition: 273. K



Loading situations

TRANSPORTATION AND DYNAMIC

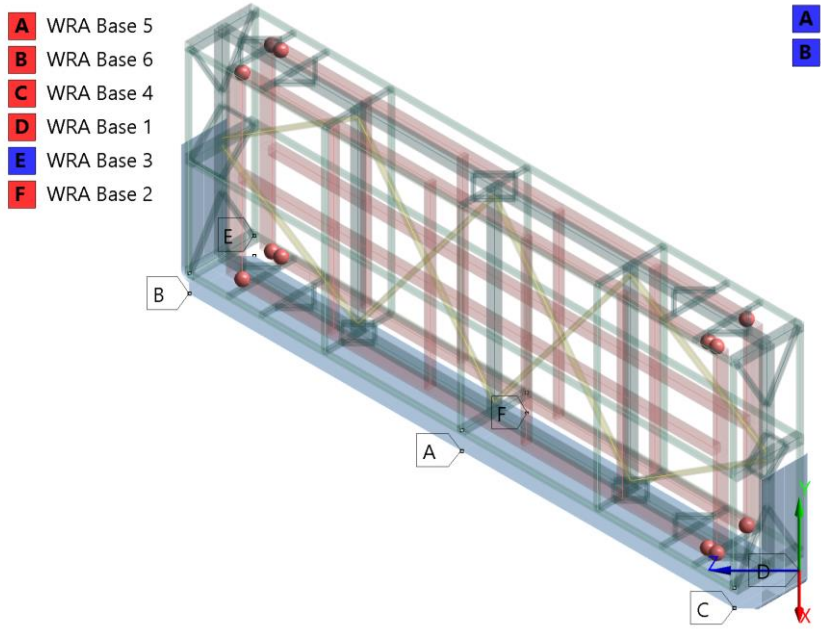
VII. ASF during transportation – quasi-static load cases.

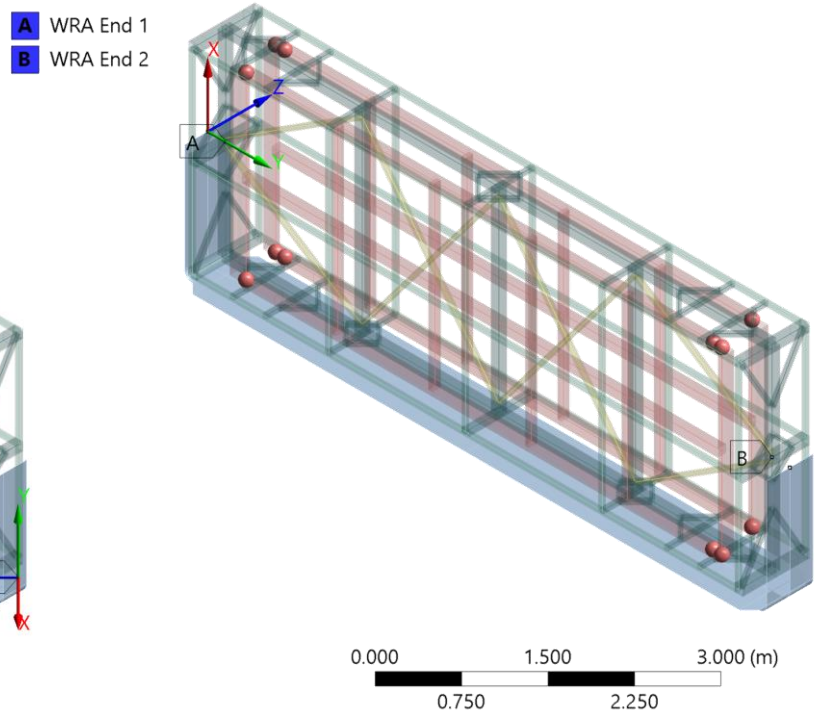
VIII. ASF during transportation – random vibrations

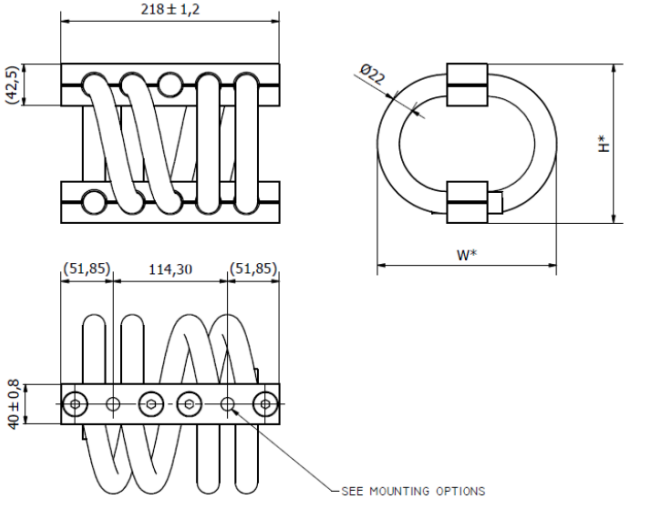
IX. ASF during transportation –sine vibrations

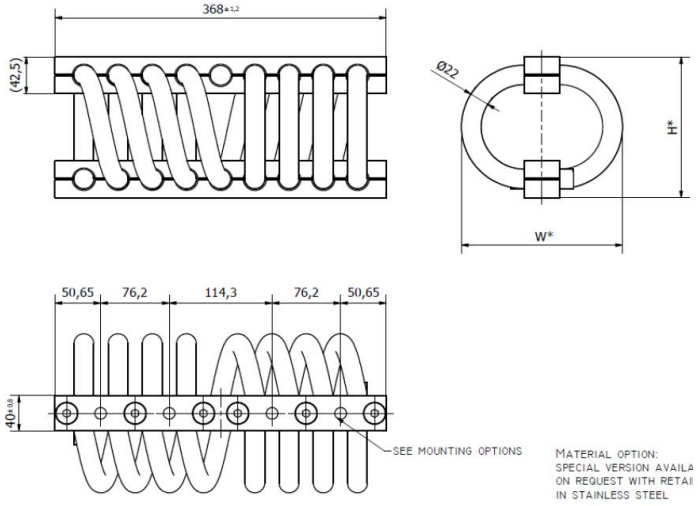
X. ASF during transportation – transportation shock

XI. ASF Handling - drop





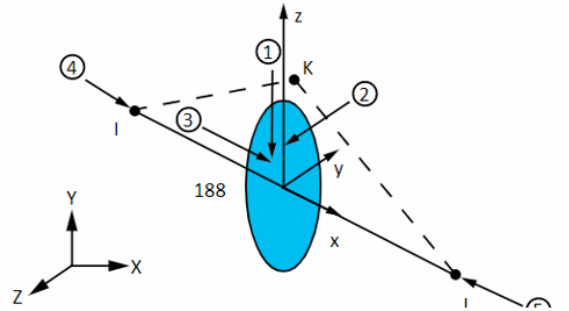


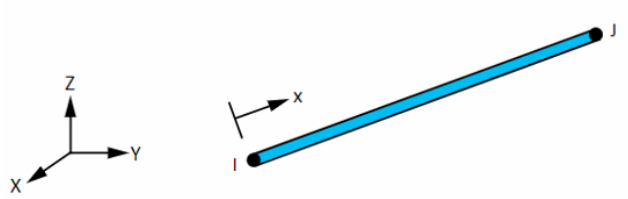


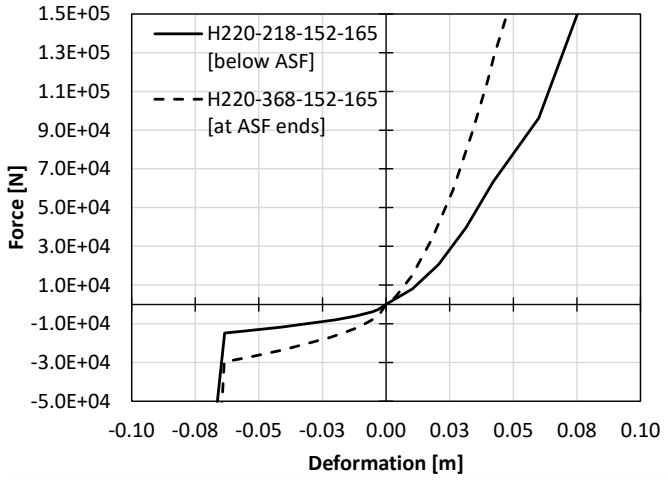
Structural analysis

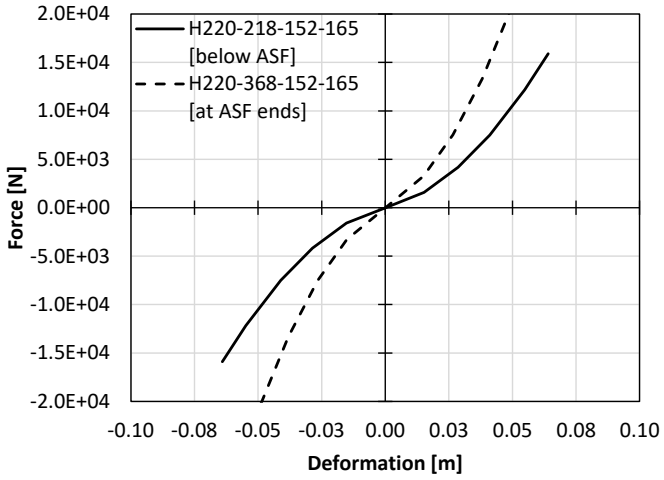
Modelling assumptions

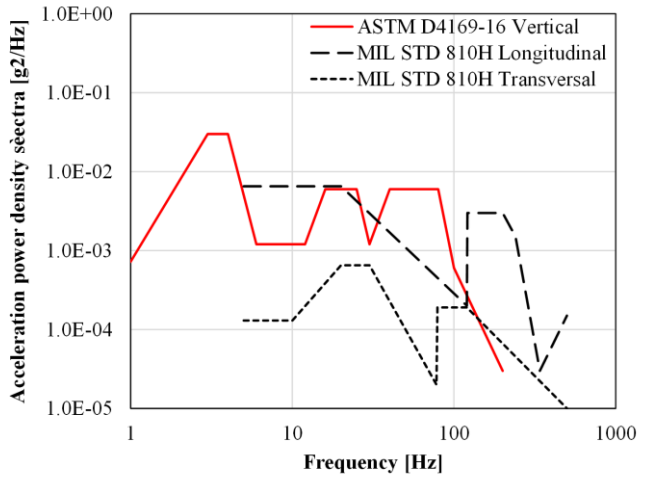
- *Software: **Ansys***
- *Beam elements*
- *Connections modelled as joints*
- *APAs are included*
- *Nonlinear absorber behaviour*
- *Base structure assumed rigid*
- *Analysis selected function of loading:*
  - *Static Structural*
  - *Random Vibrations*
  - *Harmonic Response*
  - *Transient*

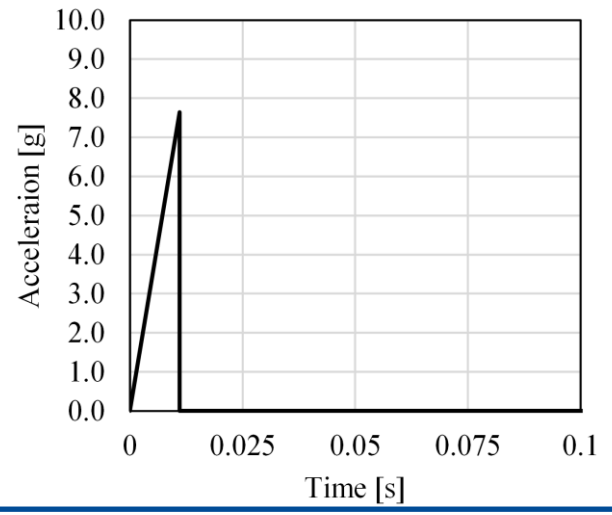












Design Requirements for the ASF (see previous presentation)

- To be easily handled in all lifting situations and able to withstand 1.5 x Static Load for these cases (code requirement for lifting tools).
- Meet the requirements for critical lift
- To withstand dynamic inputs (accelerations, vibration, shock) and reduce their transfer to the APAs
- To be able to withstand accidental cases (Ross shaft hoist failure, accidental drop)
- Protect from impacts and environmental effects
- Ease of access to the APA for verifications
- Ease of installation of the APA at the factory and removal inside the cavern

Codes for the ASF design

The applicable standards for design, fabrication, and quality assurance of the APA shipping frame are listed below:

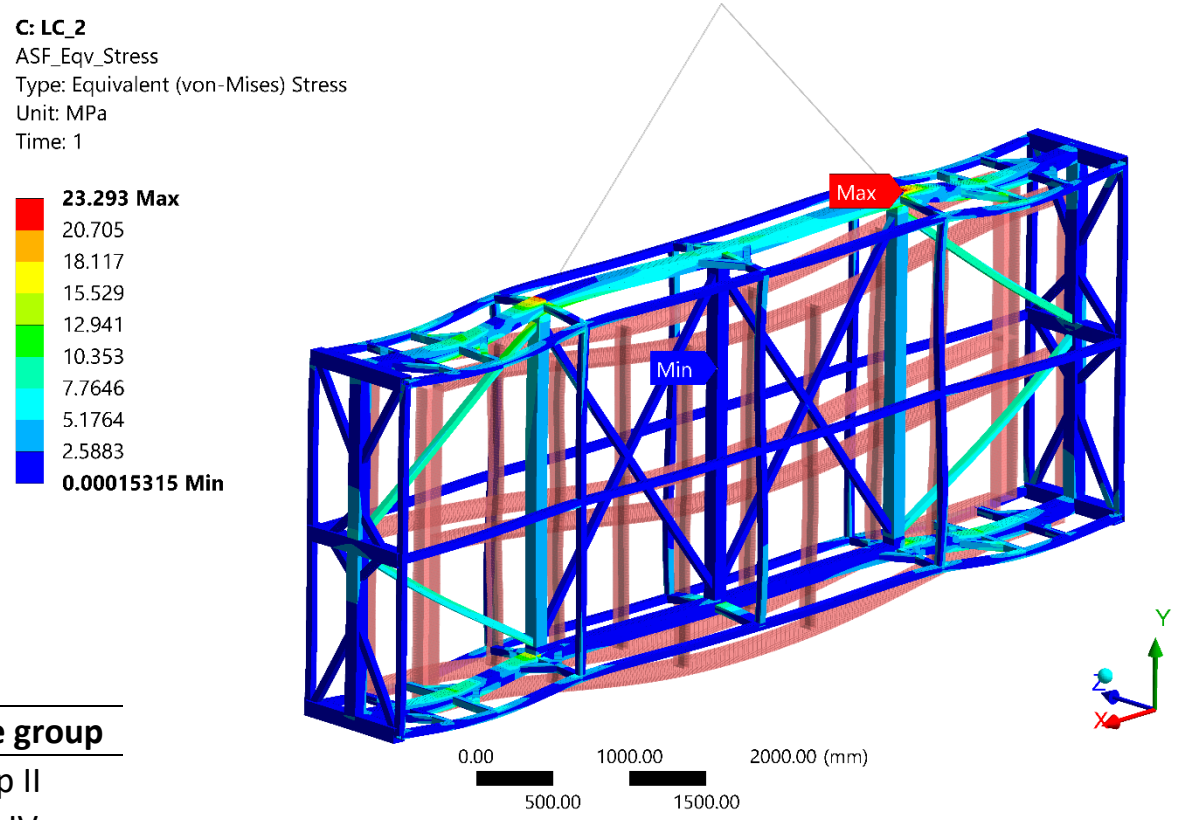
- ASME B30.20-2013 (Below-the-hook lifting devices)
- ASME BTH-1-2017 (Design of Below-the-Hook Lifting Devices)
- ANSI/AISC 360 (Specification for Structural Steel Buildings)
- Structural Welding Codes: ANSI/AWS D14.1
- ASTM D4169 Standard testing for Performance testing of shipping containers and systems
- MIL STD 810H - DOD Test methods standard

All member and connection checks were carried out in accordance to ASME BTH-1 for the lifting cases and AISC360-1 for the Transportation and accidental cases

Results and Verifications – STATIC/LIFTING

Maximum Equivalent stress

Load case group	FEA Von Misses stress $\sigma_{equiv.max}$ [MPa]	Allowable stress F_{cr} [MPa]	Utilization ratio [-]
Group I	16.8	177.5	0.09
Group II	23.3	177.5	0.13
Group III	21.3	177.5	0.12
Group IVa	21.0	177.5	0.12
Group IVb	42.1	319.5	0.13
Group V	6.7	177.5	0.04
Group VI	18.5	177.5	0.10



Maximum verification utilization ratios

Maximum uitilisation ratios for member checks – design load cases (static)

Section	UR	Stress state	Load case group
2x2x3/16	0.36	Compression + Bending	Group II
4x4x3/16	0.26	Shear Z	Group IVa
4x2x3/16	0.08	Combined normal and shear stresses	Group II

Note that a UR <1 means that the verification is passed.

Results and Verifications – STATIC/LIFTING - Accidental

Maximum Equivalent stress

Load case group	FEA Von Misses stress $\sigma_{equiv.max}$ [MPa]	Allowable stress F_{cr} [MPa]	Utilization ratio [-]
Group I	16.8	177.5	0.09
Group II	23.3	177.5	0.13
Group III	21.3	177.5	0.12
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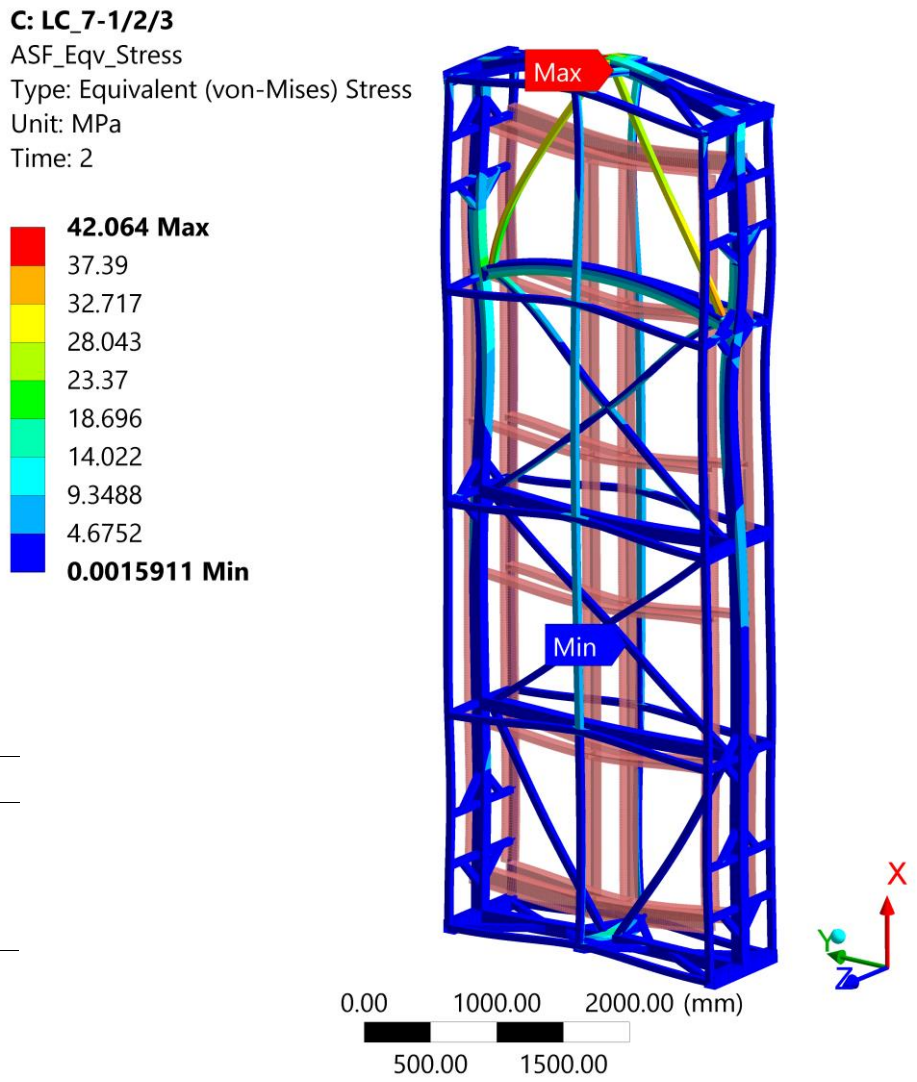


Maximum verification utilization ratios

Section	UR	Stress state	Load case group
2x2x3/16	0.19	Tension + Bending	
4x4x3/16	0.28	Shear Z	Group IVb
4x2x3/16	0.02	Compression + Bending	

Note that a UR <1 means that the verification is passed.

Results and Verifications – STATIC/LIFTING

Connections

Maximum utilization ratios

Maximum bolted connection utilization ratios for static LCs

Connection	V_{Rd}	N_{Rd}	Design LC Groups		Accidental LC – Group IVb
			UR	Group	UR
	[kN]	*[kN]*	*[-]*	*[-]*	*[-]*
1	38.8	24	0.13	Group III	0.17
2	15.5	21.6	0.14	Group I	0.11
3-A	31.1	37.9	0.03	Group II	0.01
3-B	46.6	24	0.10	Group II	0.06
4-A	31.1	24.7	0.03	Group III	0.02
4-B	31.1	20.4	0.12	Group IVa	0.15
4-C	15.5	27.9	0.06	Group II	0.01
4-D	31.1	55.2	0.02	Group II	0.00
5	5.2	6.8	0.48	Group V	0.10
6	43.6		0.05	Group II	

V_{Rd} – shear resistance of the bolted connection
N_{Rd} – tensile resistance of the bolted connection

Welds maximum uitilisation ratios for static LCs

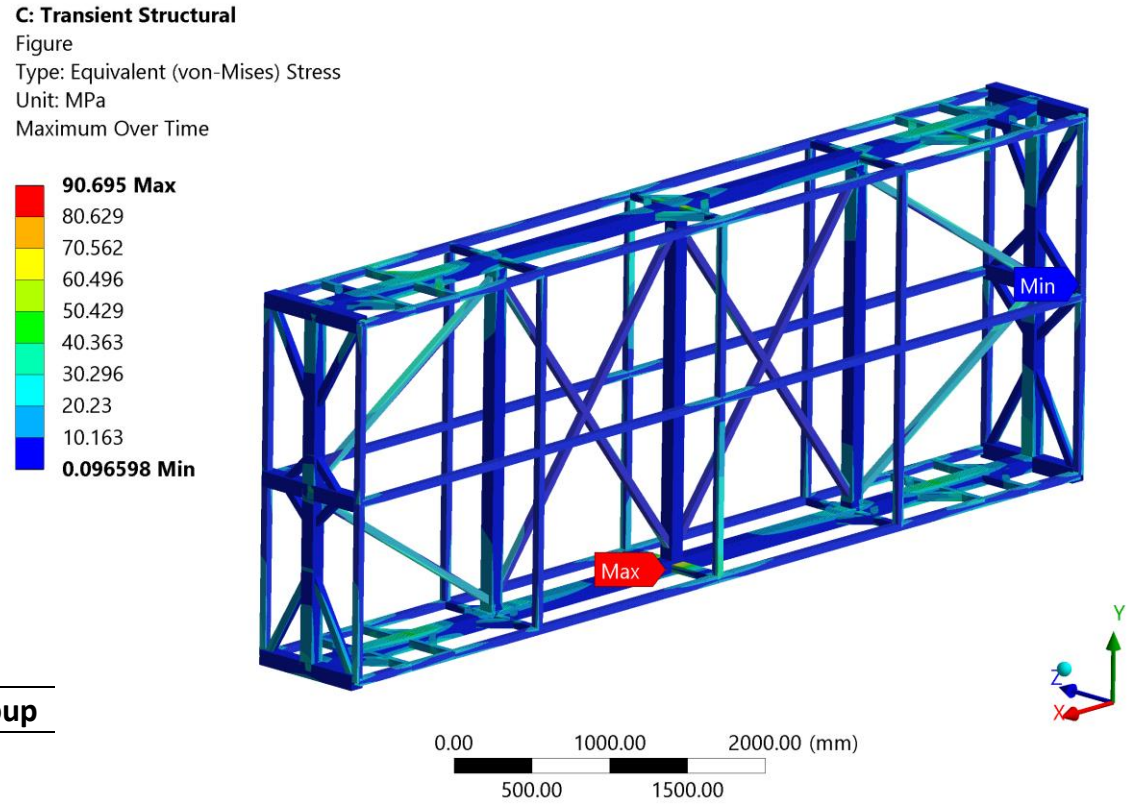
Weld configuration	Design LC Groups			Accidental LC – Group IVb	
	f_{cr} *[MPa]*	UR	Group	f_{cr} *[MPa]*	UR
Welds "4x2" to "4x4"	15.3	0.10	Group II	12.6	0.05
Welds "4x4" to "4x4"	40.1	0.27	Group III	72.1	0.27
Welds "2x2" to "2x2"	40.9	0.28	Group II	39.1	0.15
Welds "2x2" to "4x4"	43.8	0.30	Group III	73.4	0.28
Welds "2x2" angle to plate	35.7	0.24	Group I	35.8	0.13

Note that a UR <1 means that the verification is passed.

Results and Verifications – DYNAMIC/TRANSPORTATION

Maximum Equivalent stress

Load case group		FEA Von Misses stress $\sigma_{equiv.max}$	Allowable stress F_{cr}	Utilization ratio
	Direction	*[MPa]*	*[MPa]*	*[-]*
Group VII	$g_y + 0.8g_x$	26.0	320	0.09
	$g_y + 0.8g_z$	39.1		0.14
Group VIII	PSD_x	35.5		0.12
	PSD_y	27.1		0.09
	PSD_z	53.0		0.18
Group IX	Sine $0.5g_x$	41.9		0.15
	Sine $0.5g_y$	42.9		0.15
	Sine $0.5g_z$	53.0		0.18
Group X	Shock $7.6g_x$	38.5		0.13
	Shock $7.6g_x$	52.2		0.18
	Shock $7.6g_x$	57.5		0.20
Group XI	Drop u_y = 114mm	115.6		0.40



**It considers only the dynamic effect, not the static gravitational effect*

Maximum verification utilization ratios

Section	UR	Stress state	Load case group
2x2x3/16	0.66	Compression + Bending	Group XI
4x4x3/16	0.34	Compression + Bending	Group XI
4x2x3/16	0.41	Compression + Bending	Group XI

Note that a UR <1 means that the verification is passed.

Results and Verifications – DYNAMIC/TRANSPORTATION

Connections

Maximum utilization ratios

Maximum bolted connection utilization ratios for dynamic LCs

Connection	V_{Rd} *[kN]*	N_{Rd} *[kN]*	UR *[-]*	Group *[-]*
1	63.8	38.1	0.51	Group XI (Drop)
2	25.5	39	0.34	Group XI (Drop)
3-A	51	76.1	0.05	Group XI (Drop)
3-B	76.5	38.1	0.24	Group XI (Drop)
4-A	51	39.7	0.13	Group VII (Quasi-Static)
4-B	51	34.1	0.40	Group VII (Quasi-Static)
4-C	25.5	50.2	0.34	Group XI (Drop)
4-D	51	88.8	0.10	Group XI (Drop)
5	9	11.6	0.65	Group XI (Drop)
6	75.9		0.32	Group XI (Drop)

V_{Rd} – shear resistance of the bolted connection
N_{Rd} – tensile resistance of the bolted connection

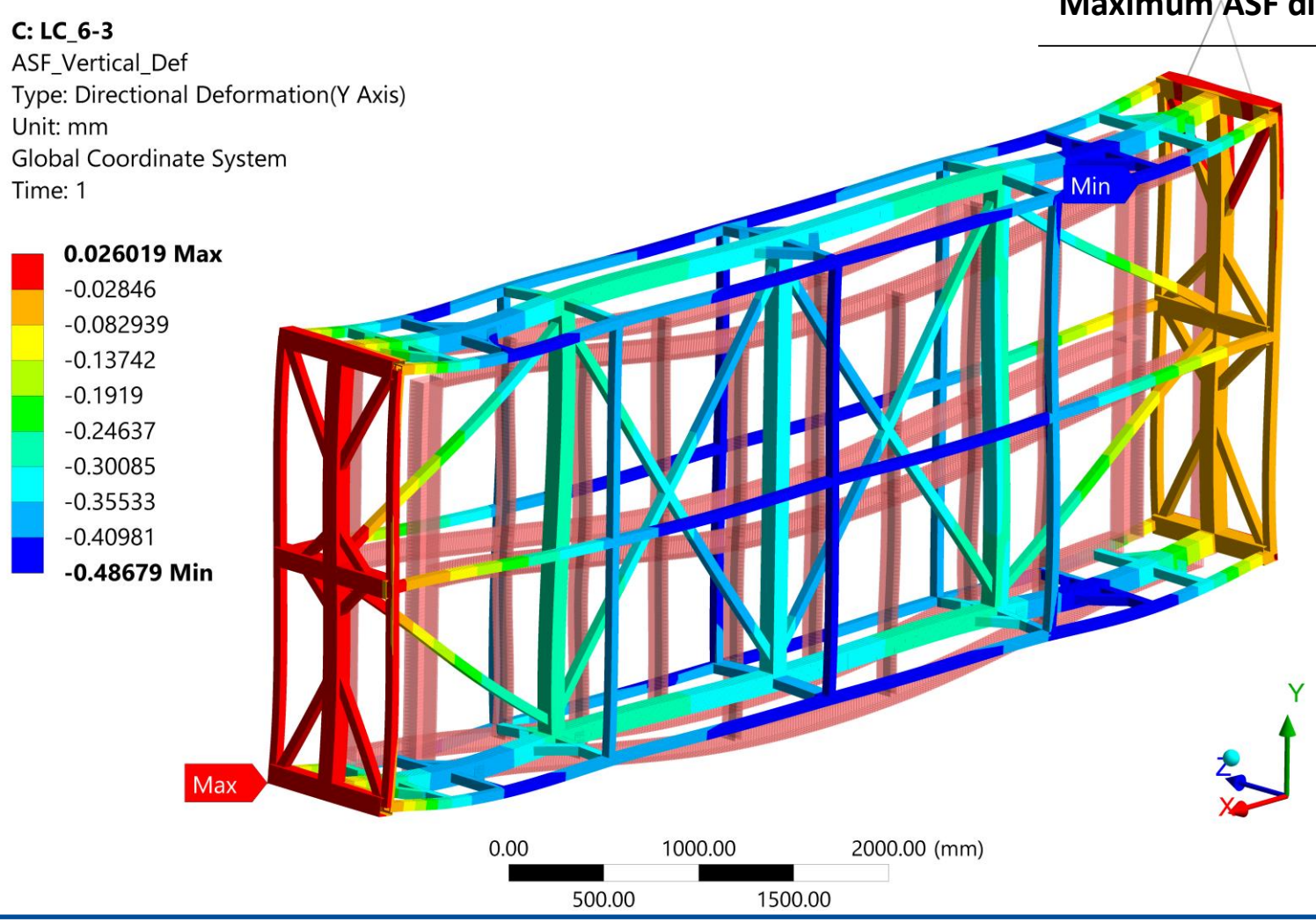
Welds maximum uitilisation ratios for dynamic LCs

Weld configuration	f_{cr} *[MPa]*	UR	Group
Welds "4x2" to "4x4"	129	0.49	Group XI (Drop)
Welds "4x4" to "4x4"	119	0.45	Group XI (Drop)
Welds "2x2" to "2x2"	195	0.73	Group XI (Drop)
Welds "2x2" to "4x4"	124	0.47	Group XI (Drop)
Welds "2x2" angle to plate	165	0.62	Group XI (Drop)

Note that a UR <1 means that the verification is passed.

ASF Deformations – STATIC/LIFTING

	Longitudinal	Vertical	Transversal
	U_x	U_y	U_z
	[mm]	*[mm]*	*[mm]*
Maximum ASF displacements	**<<1.0**	**1.0**	**<<1.0**



ASF Deformations – DYNAMIC/TRANSPORTATION

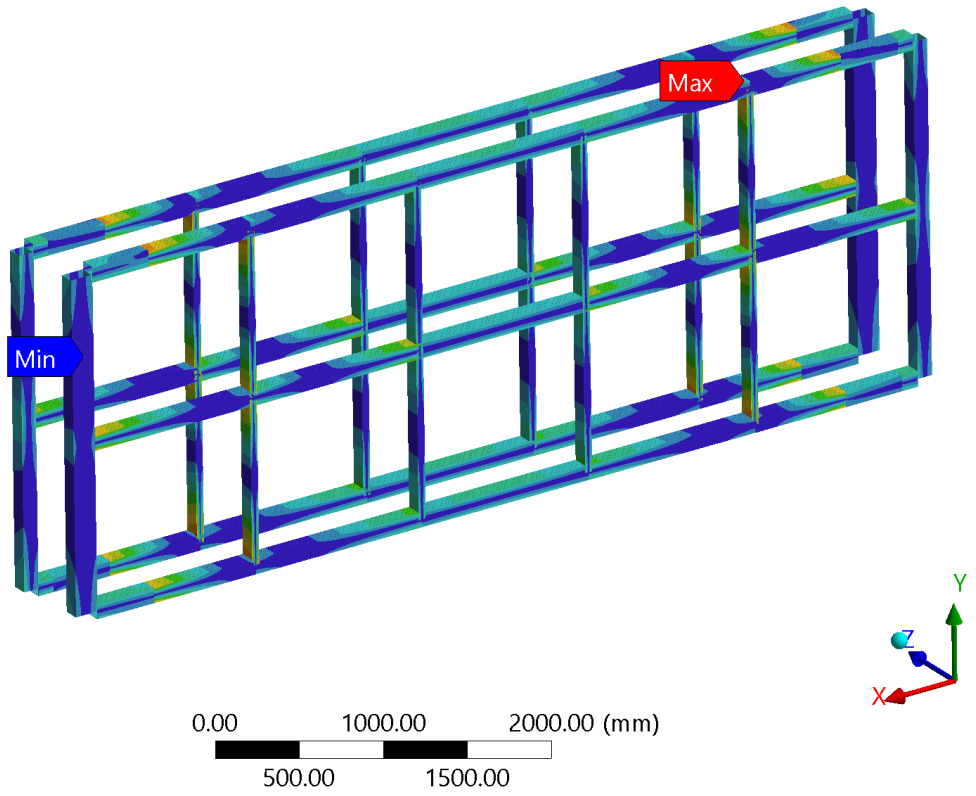
Load case group		Maximum ASF displacement		
		Longitudinal	Vertical	Transversal
		U_x	U_y	U_z
	Direction	*[mm]*	*[mm]*	*[mm]*
Group VII	$g_y + 0.8g_x$	8.9	8.1	<1.0
	$g_y + 0.8g_z$	<1.0	16.7	53.8
Group VIII	PSD_x	5.3	1.1	<1.0
	PSD_y	<1.0	4.4	<1.0
	PSD_z	<1.0	<1.0	1
Group IX	Sine $0.5g_x$	5.2	2.7	<1.0
	Sine $0.5g_y$	<1.0	7.4	<1.0
	Sine $0.5g_z$	<1.0	28.5	41.2
Group X	Shock $7.6g_x$	9.5	1.5	<1.0
	Shock $7.6g_y$	<1.0	8.4	<1.0
	Shock $7.6g_z$	<1.0	5.0	32.8
Group XI	Drop u_y = 114mm	<1.0	32.4	<1.0
Maximum ASF dynamic displacements		**9.5**	**32.4**	**53.8**

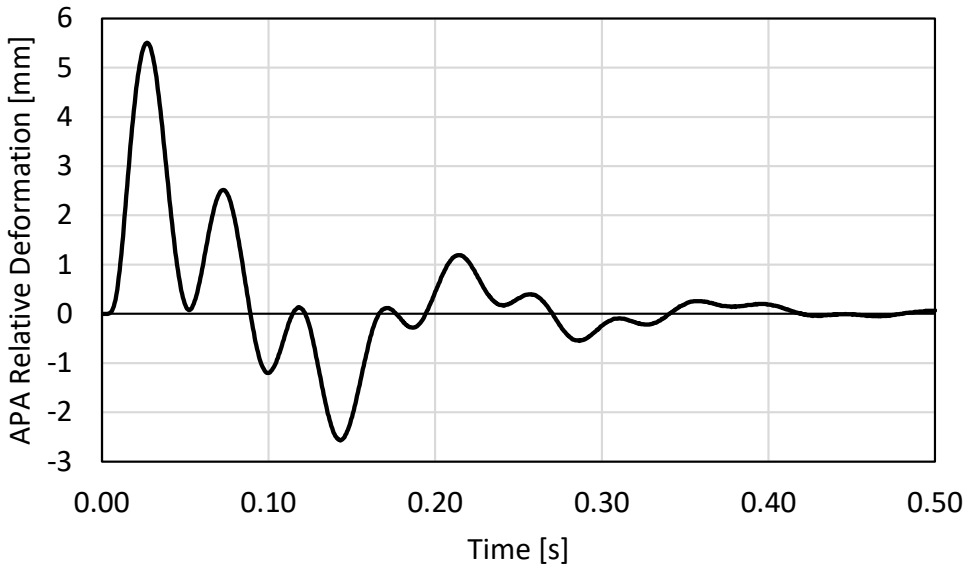
Considerations for the APA

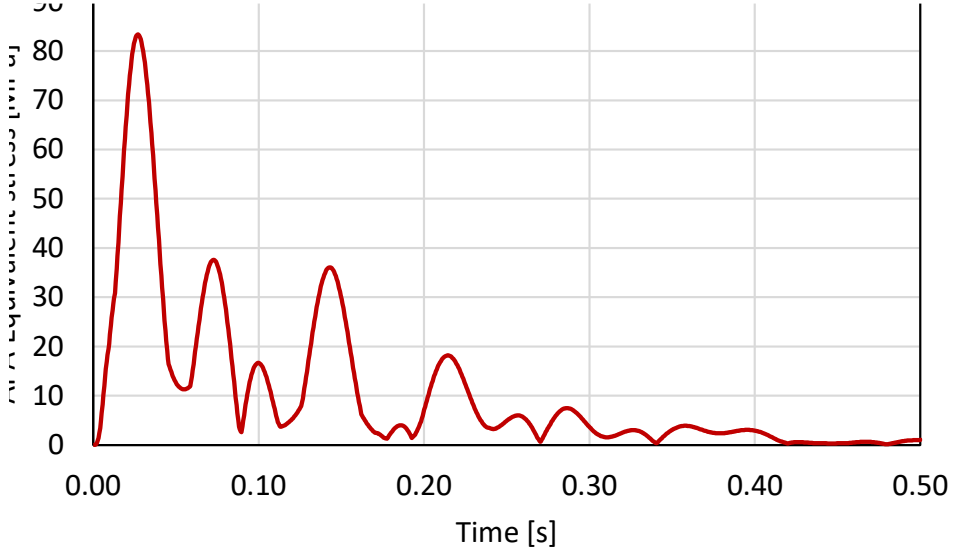
Most severe case – drop of the ASF with APA inside – safe based on preliminary assessment

C: Transient Structural
APA_Eqv_Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Maximum Over Time
Max: 83.355
Min: 0.26022

83.355
74.123
64.89
55.657
46.424
37.191
27.959
18.726
9.493
0.26022







Considerations for use

1. The analyzed boundary conditions must be replicated in reality for all cases (lifting, storage, transportation)

2. The movement of the ASF in the factory, drift and cavern should be of such nature as not to induce dynamic effects. Measures should be taken to mitigate such effects.

3. The handling of the APA Shipping Frame loaded with APA detectors must be treated as a “critical lift” (DOE-STD-1090) in all circumstances.

Conclusions

- The ASF design is deemed safe as all the member strength and stability, and connections (welded and bolted) checks are met for all LCs.
- The APAs were part of the analyzed ASF model. Based on the verifications performed, the ASF can safely hold, lift, and transport the APA detectors
- The AVMR assessment of the transportation assembly (ASF and absorbers) confirmed it meets the safety requirements for transportation.

Note: The ASF was designed and verified based on the US codes for lifting and steel structures. Another set of verifications was performed in accordance with the EU equivalent codes and very similar results were obtained.

Next steps

- An envelope study is being performed to verify the APA and shipping frame
- A prototype is being built at CERN (whcihc will be surveyed for execution tolerances) and two are being built in the UK.
- A test plan is being developed
- The CERN prototype will be loaded with old ProtoDUNE APAs, instrumented and once tested, it will be shipped to SURF