EUROfusion

EUROfusion WP-DIV-IDTT-MidTerm Meeting 2023

DTT Divertor advancements in design and technology R&D

Design of the divertor support structures and cassette CAD modelling

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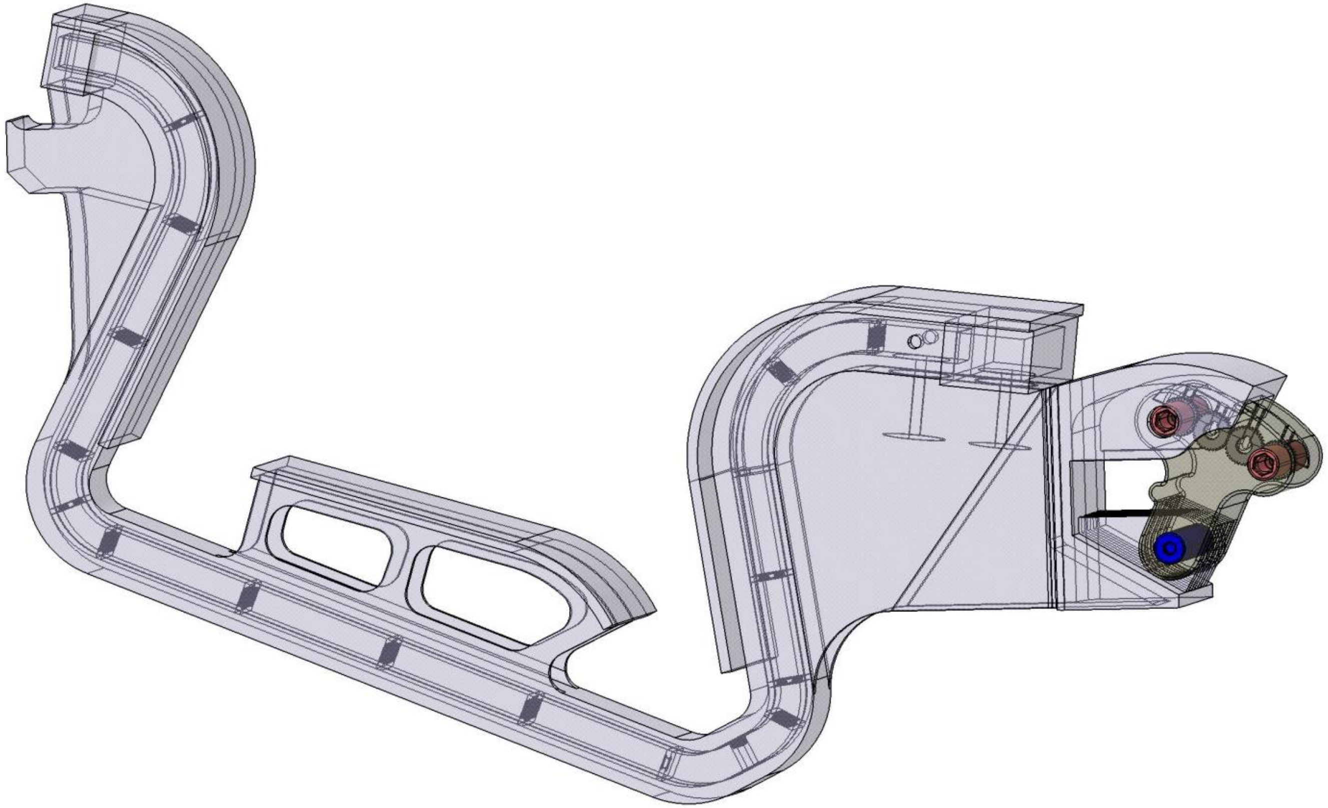
Outline

- Objectives
- Alternative solutions for Divertor Outboard Fixation System
- Main components of Knuckle Device
- Brief overview on the set of mounting operations of Knuckle
- FE Analysis on the whole Divertor-Knuckle structure
- FE Submodeling analysis: Knuckle shafts geometry optimization and validation through ITER SDC-IC
- Conclusions

Objectives

Update of the divertor CAD model for EM analyses *and divertor optimization for structural and thermo-hydraulic performances.* ***Development of divertor fixation to VV****: compatibility with RH operations and with VV interfaces.*



Engineering design of Divertor fixation system

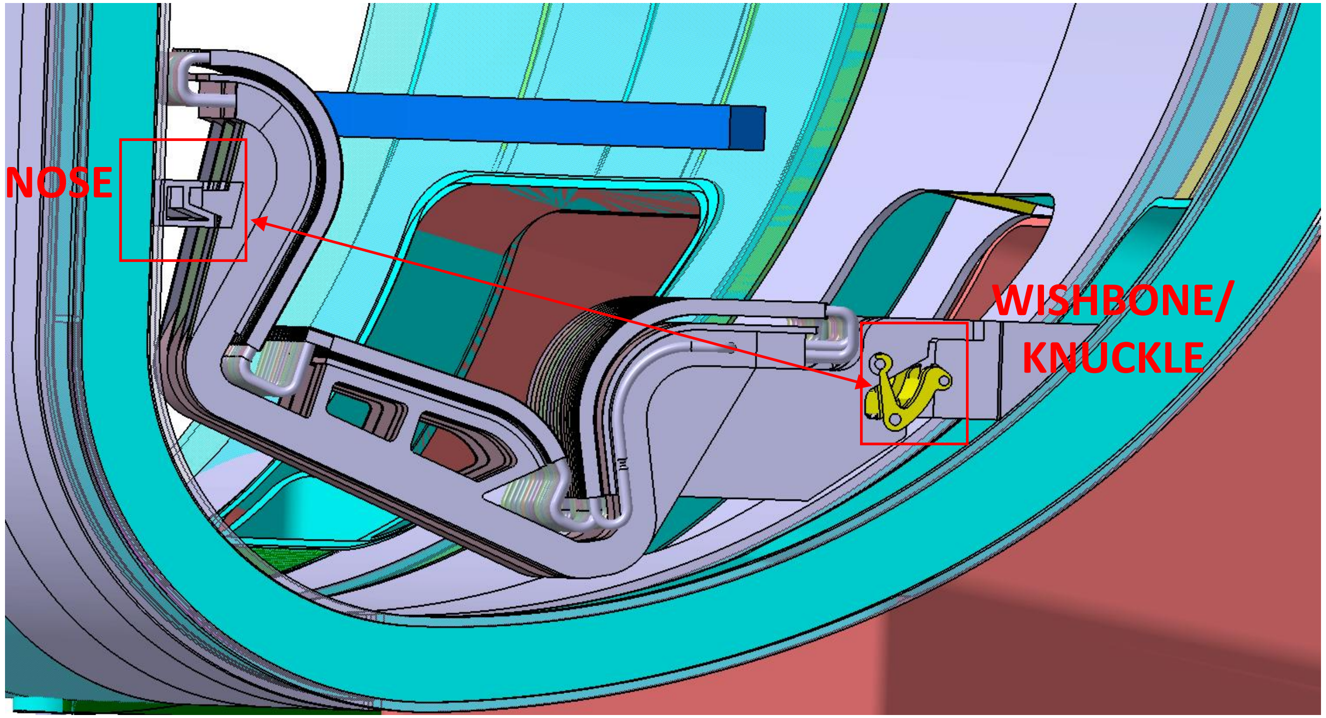
Requirements:

- Allows for toroidal transport
- Provide sufficient **clearance during divertor transport**
- Lock the divertor cassette body to the vacuum vessel
- **Ensure electrical contact** in any load condition during plasma operation
- Transfer load to VV under any load condition
- Carry the maximum halo and eddy currents in the VDEs
- Compatibility with remote handling.
- The fixing system shall avoid any vibrations

Engineering design of Divertor fixation system

Divertor is fixed in position as pre-compressed structure between inboard-outboard.

- Inboard: «Nose»
- Outboard: «Wishbone/Knuckle»

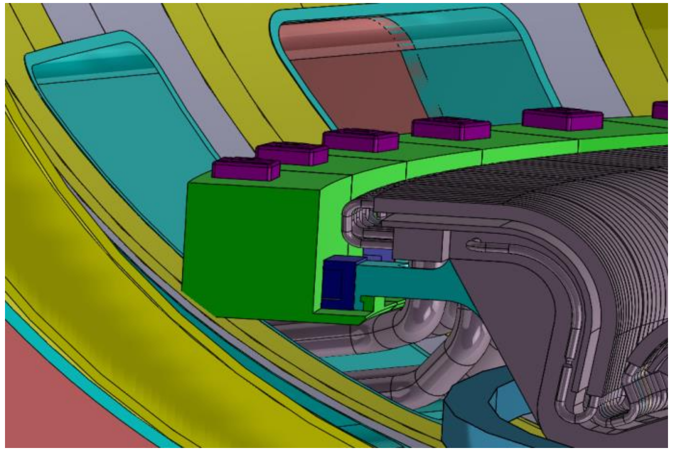


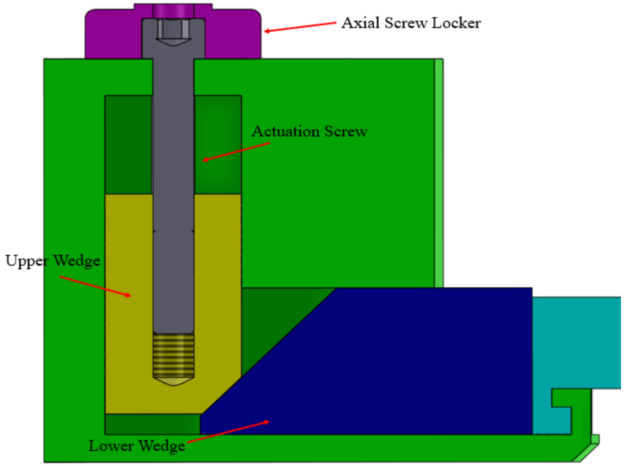
!!Wishbone has been re-evaluated at the end of 2022 due to cassette flexibility and RH operations!!

Fixation System Alternatives

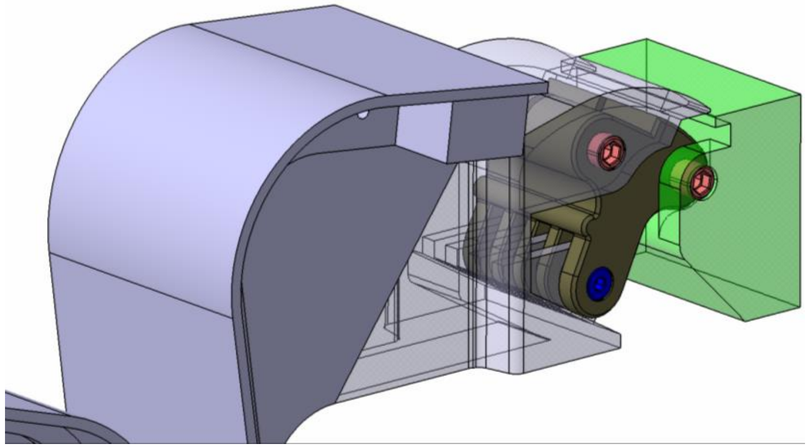
Several alternatives considered from 2022: DIV-IDTT.S.01b-T002-D001_Engineering design of Divertor fixation systems_ENEA (2QADH2)

Options selected for further development





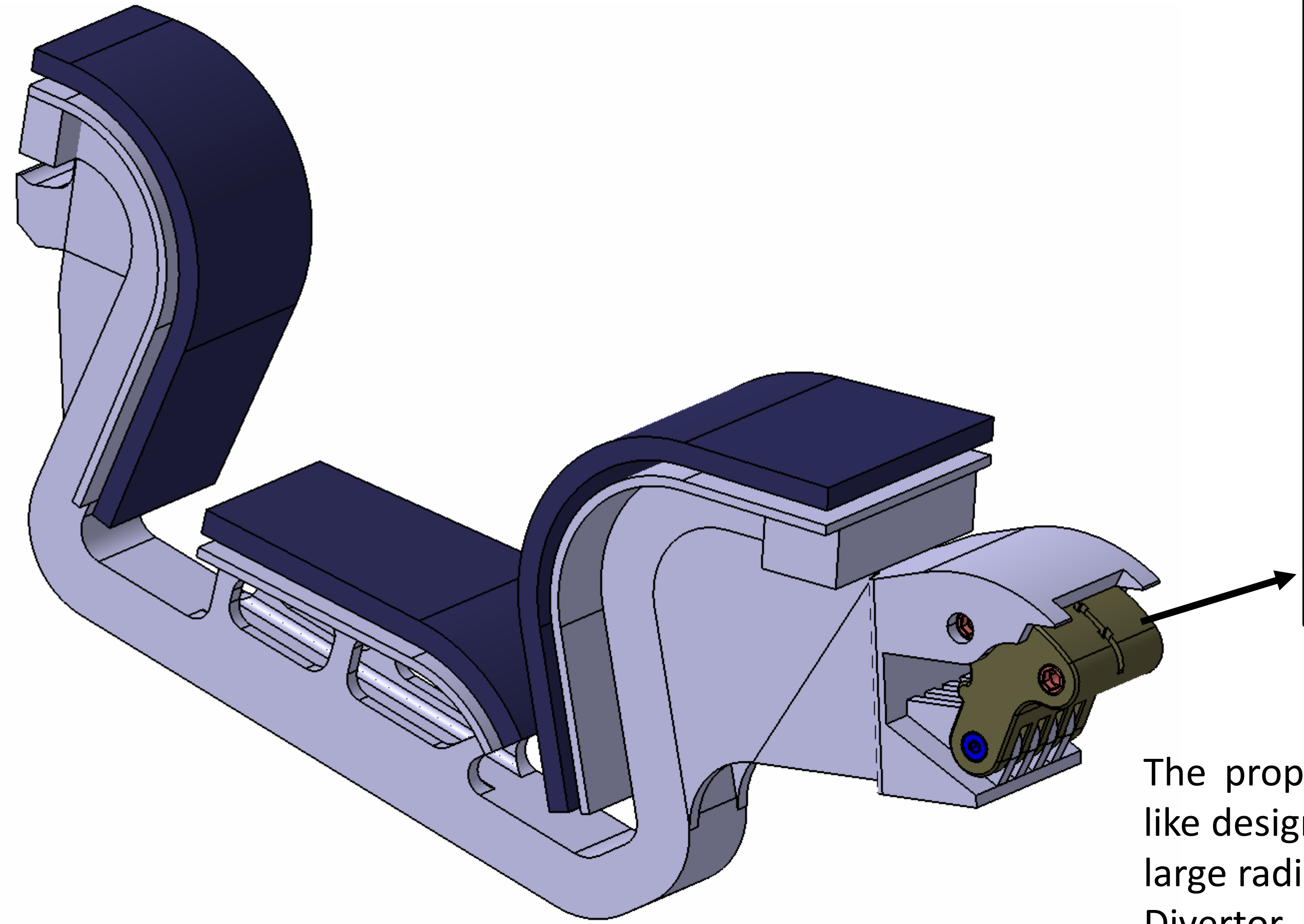
Wedges Fixation System: Through a wedges mechanism the Divertor Cassette Body is preloaded and locked in position.

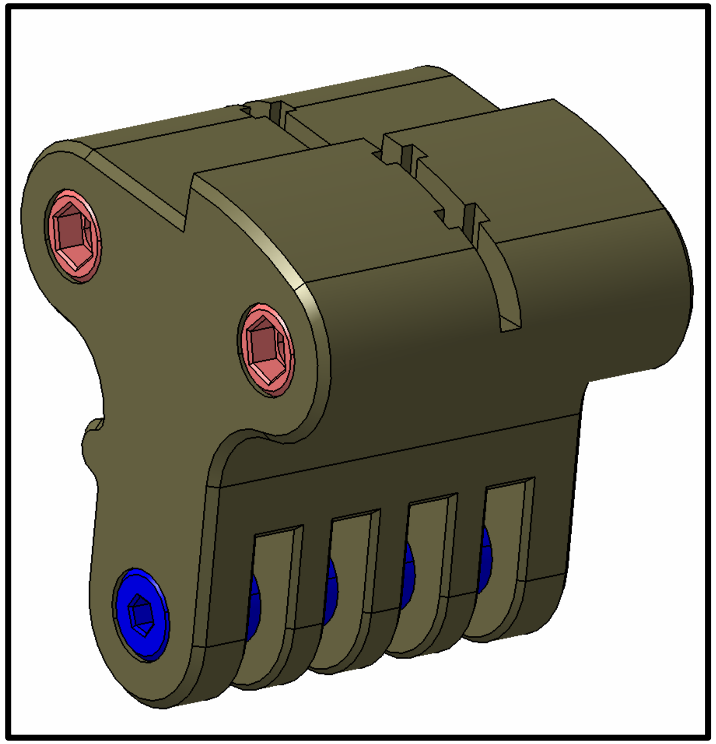


ITER-like Knuckle Locking System

Baseline solution

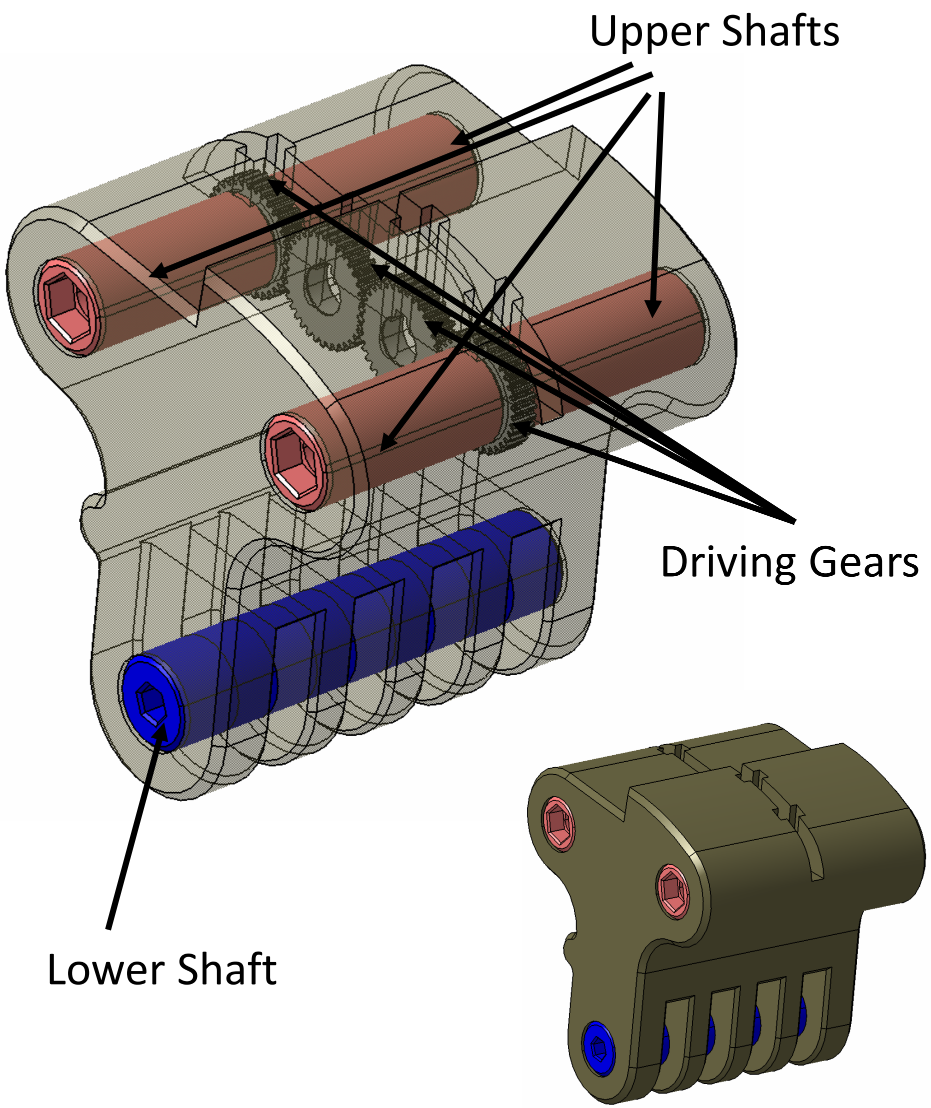
Knuckle Locking System





The proposed Outboard Locking System is an ITER-like design solution (**Knuckle**). It is designed to ensure large radial gaps during toroidal handling, preload the Divertor Cassette Body, engage the Divertor in position.

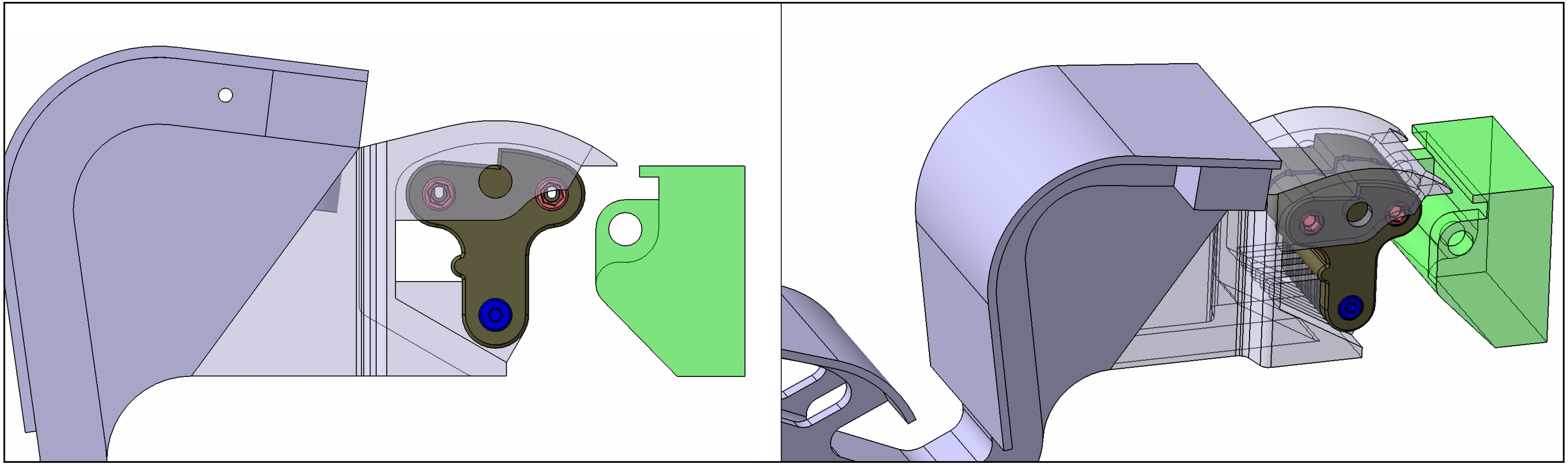
Device Components Overview



Component	Material	Description and functionality
Main Body	NiAlBr Alloy	It's the main part of the Knuckle System (146 mm of toroidal width)
Upper Shafts	Inconel 718	They are hollow in order to be screwed on the inner threaded rods. The rear ones fully engage Knuckle on the Divertor, while the front ones engage Knuckle on the Outboard Rail (30 mm external diameter, 14 mm internal diameter)
Lower Shaft	Inconel 718	It's rigidly connected to Knuckle. Through its rotation Knuckle is first partially engaged on the Outboard Rail.
Threaded Rod (Not shown in the model)	---------------	Both rear and front shafts are screwed on them. Through their rotation, the shafts unscrew and engage the respective mounting holes
Driving Gears	---------------	They connect the motion of the rear threaded rod and the front one. During the engagement of the system, only the rear rod is actuated while the front one is driven by it.

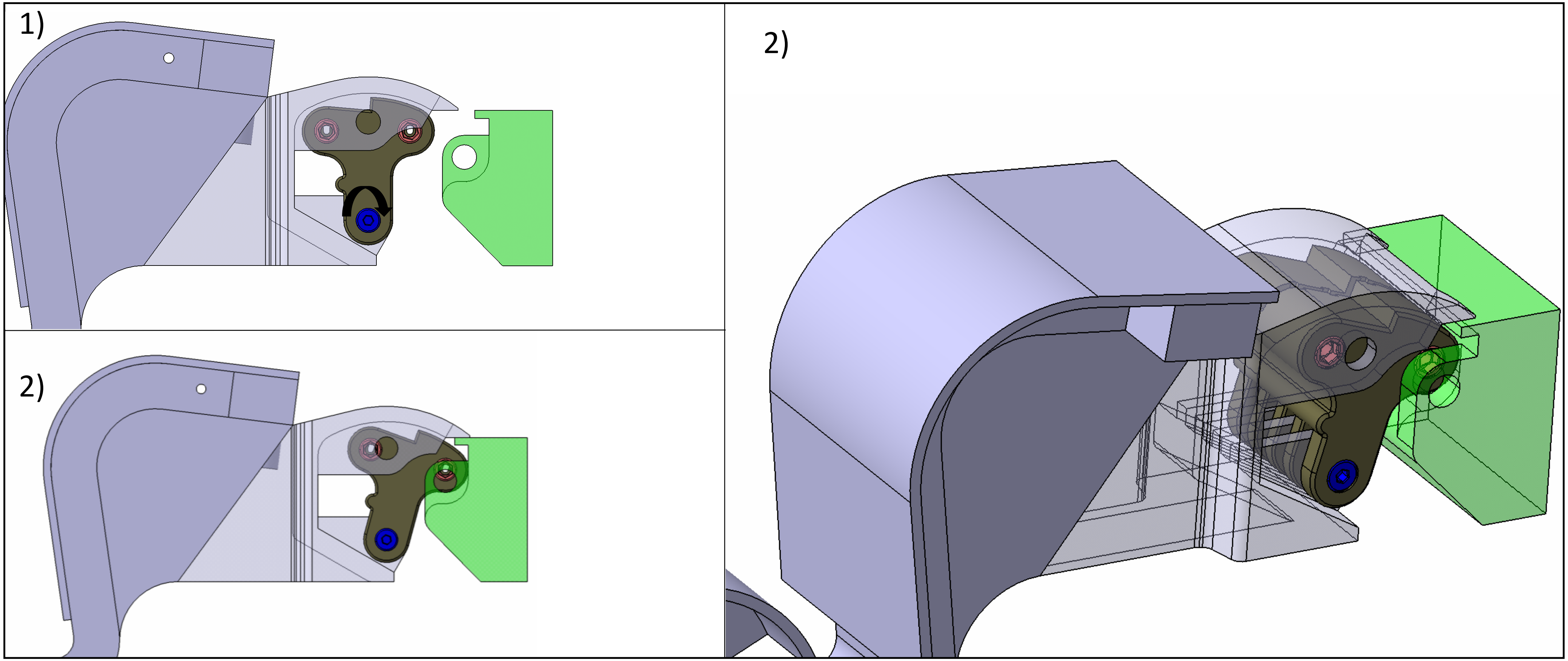
Mounting Operations

During the cassette toroidal handling, Knuckle is “rotated on the cassette”, to avoid any clashes whit other in vessel components.



Mounting Operations

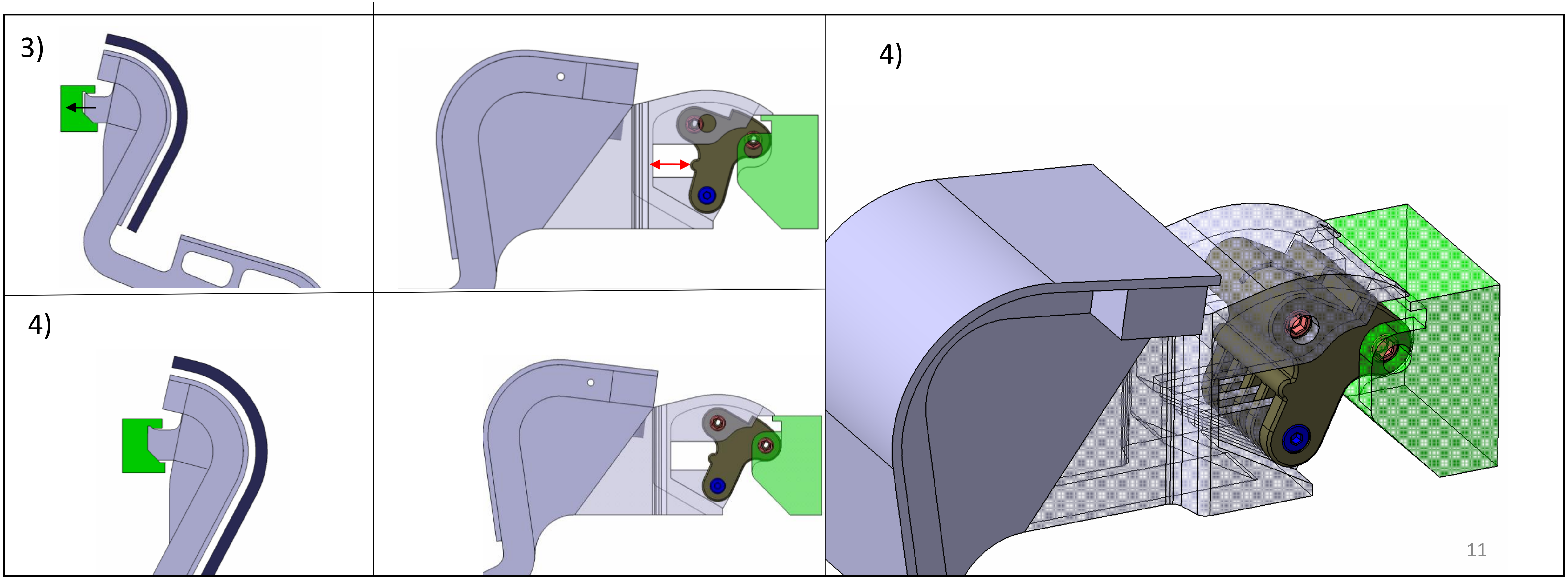
1) When the proper toroidal position is reached, the Lower Shaft is rotated and Knuckle with it.
2) The front part of Knuckle is made match with the suited Outboard Rail Vertical Interface. In this configuration the rear and front pin axes are not aligned with the respective hole's axis



Mounting Operations

3) An hydraulic or electric jack is placed between Knuckle and the Divertor Cassette Body. The jack pushes until Knuckle matches the suited slot on the Outboard Rail.

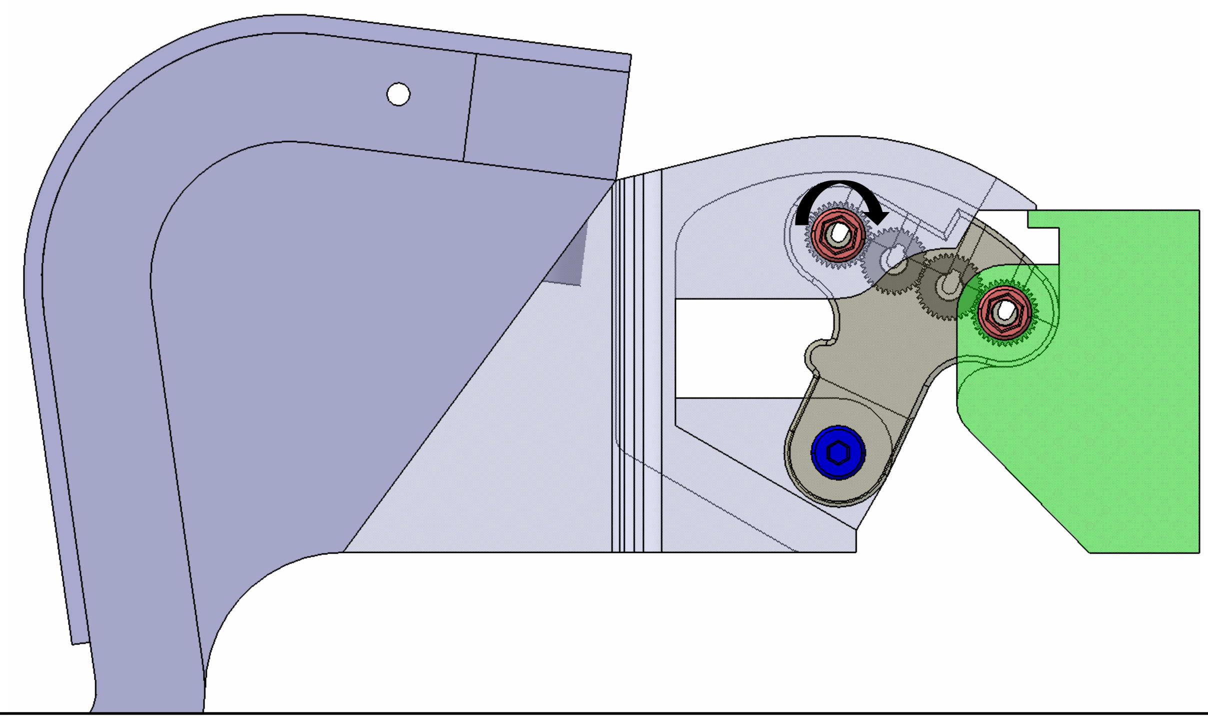
4) During the whole operation the vertical interface countered the preload action. In a first phase the Divertor Cassette Body rigidly translates, and the Nose is engaged on the Inboard Rail. After it, the “real” preloading phase starts and it last until Knuckle matches the suited complementary interface on the Outboard Rail while the shafts align with their mounting holes.



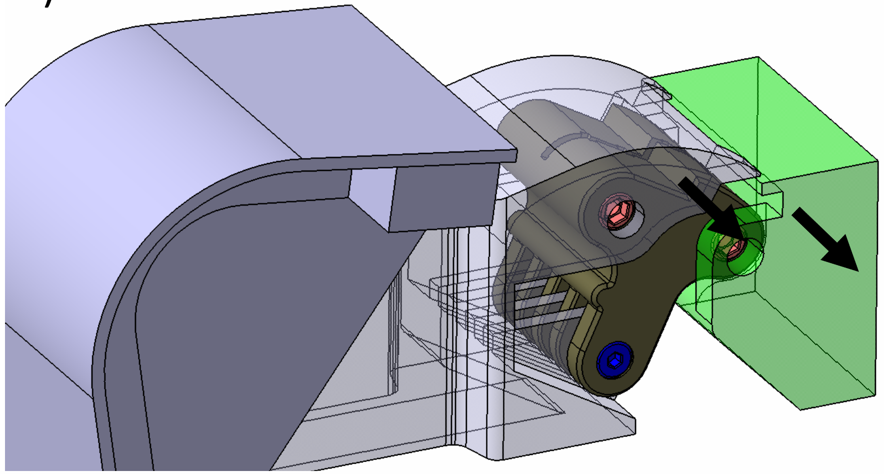
Mounting Operations

5) The rotation of the rear Threaded Rod, drives the rotation of the Driving Gears which move the front Threaded rod. 6) Therefore, just actuating the front Threaded Rod, both front shafts and rear shafts are engaged in their mounting holes

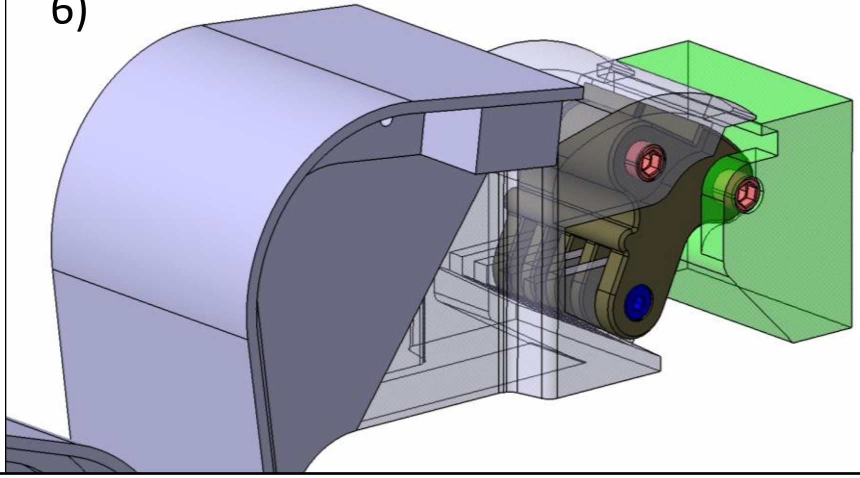
5)



5)

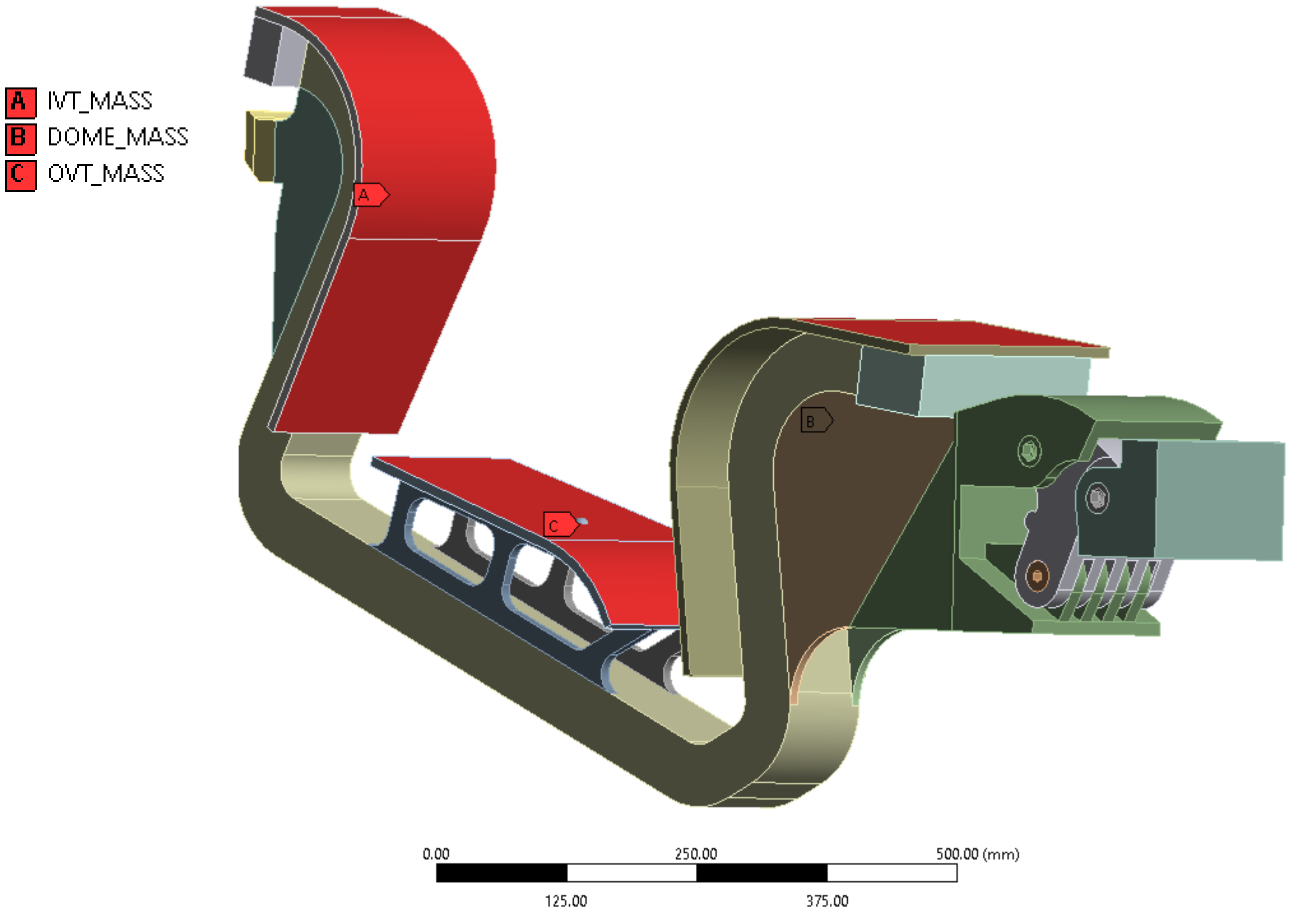


6)



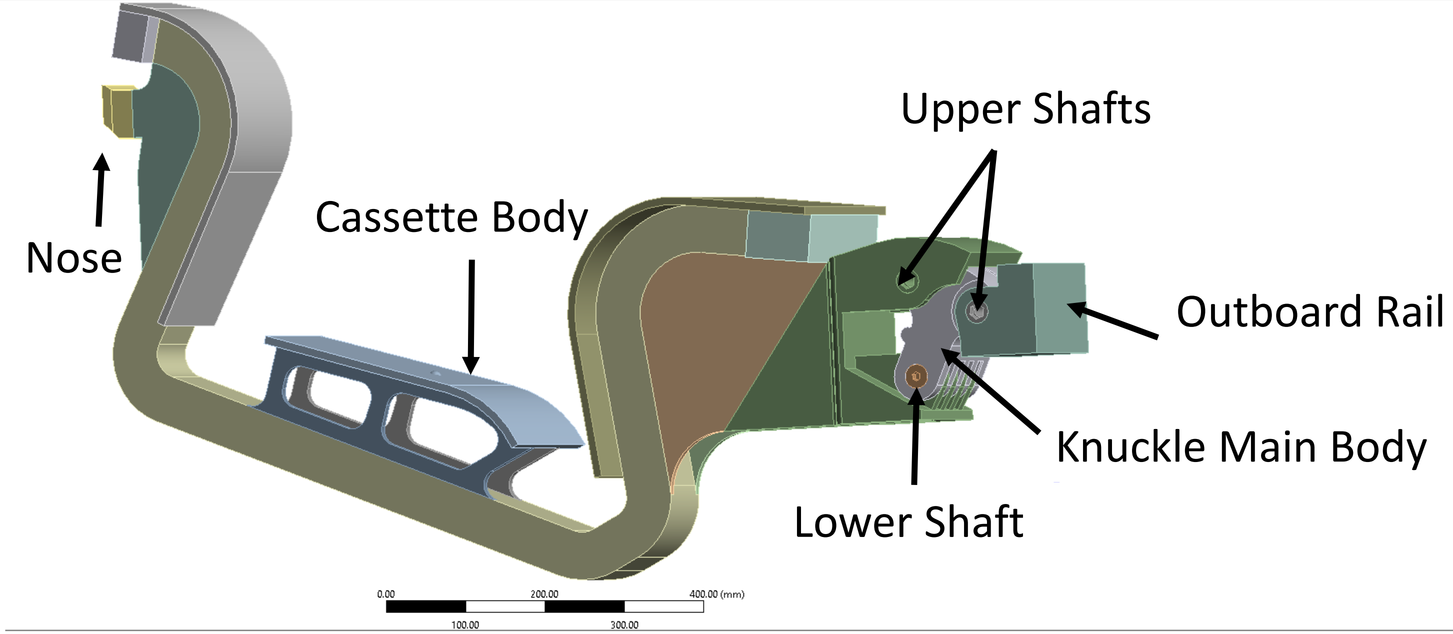
Global FE Model: Geometry

Cassette Body Mass + Knuckle	OVT Mass (A)	IVT Mass (B)	DOME Mass (C)	M_{tot}
143 kg	75 kg	40 kg	48 kg	306 kg



Note: **The masses of the PFC are simulated using concentrated masses referred to the respective supporting structure.**

Global FE Model: Materials

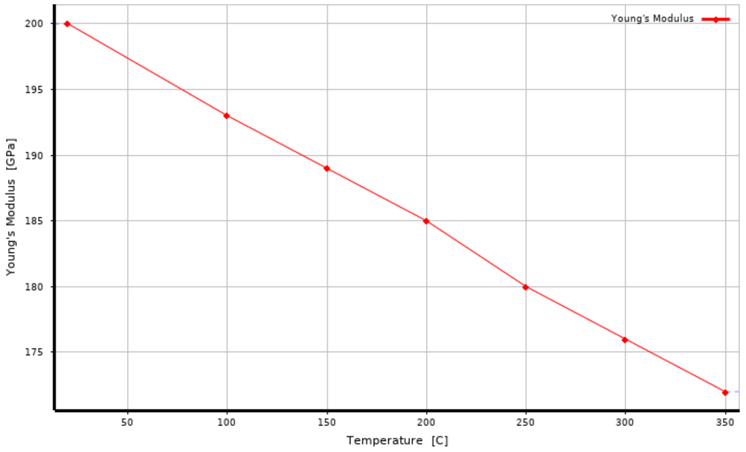


Component	Material	Sy [Mpa] (130°C)	Sm [Mpa] (130°C)
Knuckle Main Body	NiAlBr Alloy	286	195
Upper Shafts	Inconel 718	1049	425
Lower Shaft	Inconel 718	1049	425
Cassette Body	AISI 316 L IG	200	147
Outboard Rail (dummy)	AISI 316 L IG	200	147
Nose	NiAlBr Alloy	286	195

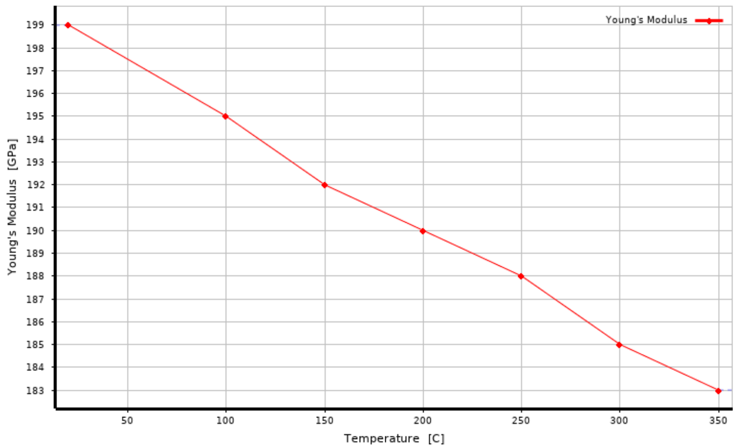
(ref. Appendix_A,_Materials_Design_Limit_Data_222RLN_v3_3)

- Young Modulus (T) (Set up in Workbench Engineering Data)

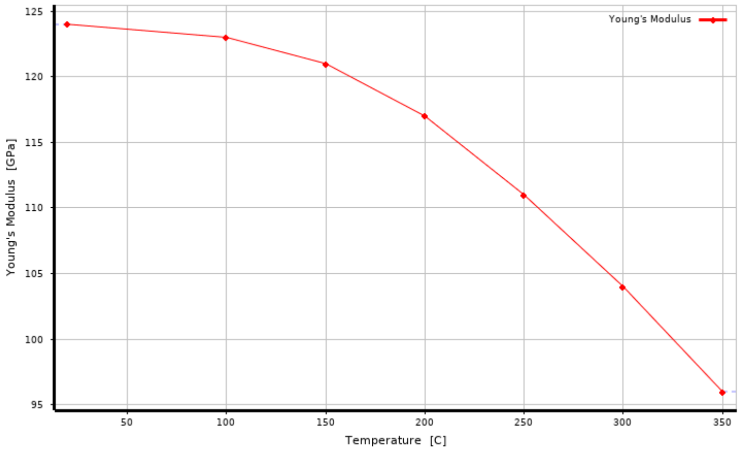
AISI 316 L IG



Inconel 718



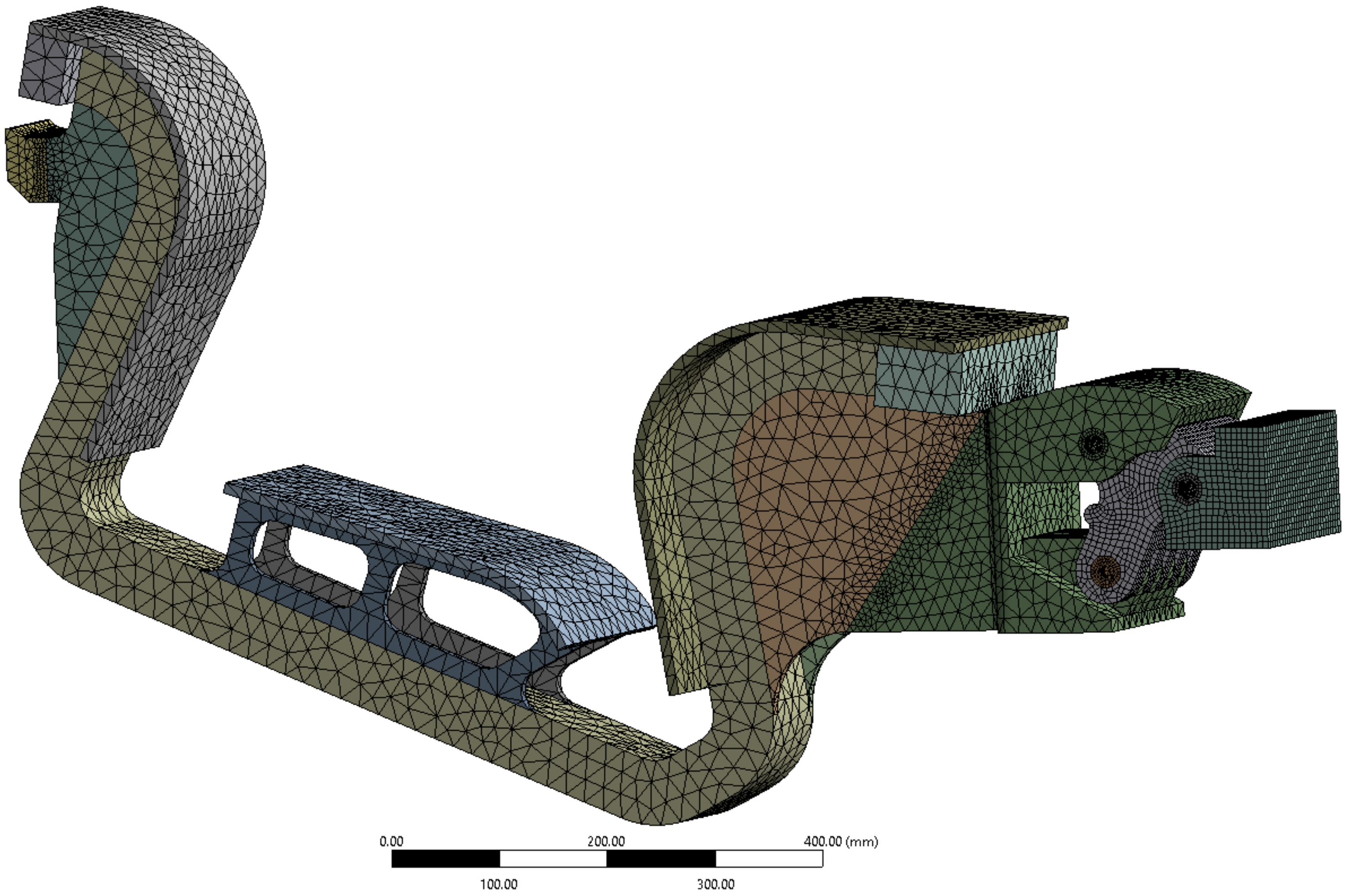
NiAlBr Alloy

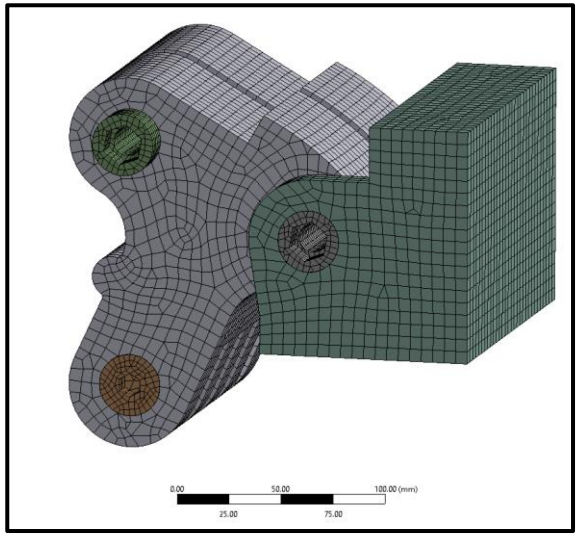


(ref. Appendix_A,_Materials_Design_Limit_Data_222RLN_v3_3)

Global FE Model: Mesh

To catch the stiffness of the Cassette Body and the displacements which it undergoes due to the imposed load configuration, a coarse mesh has been generated. The mesh include 278533 nodes and 106028 elements (quadratic elements type).

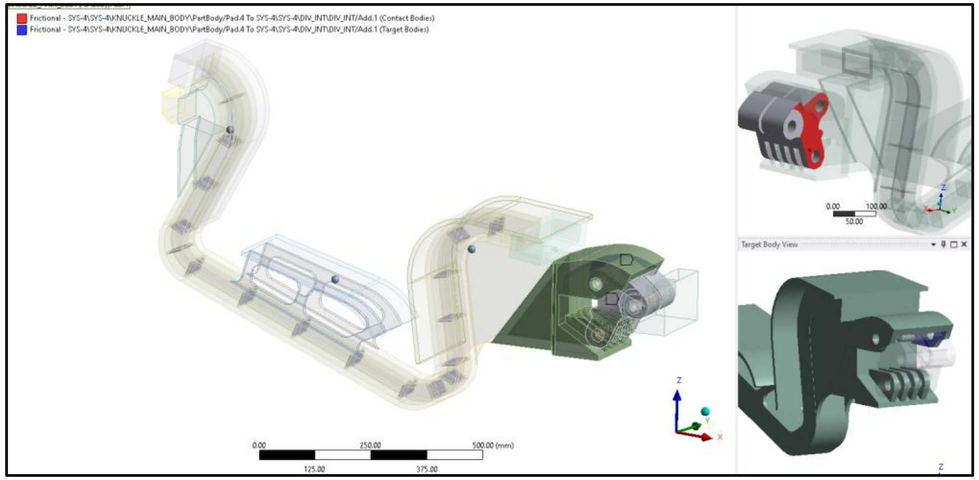


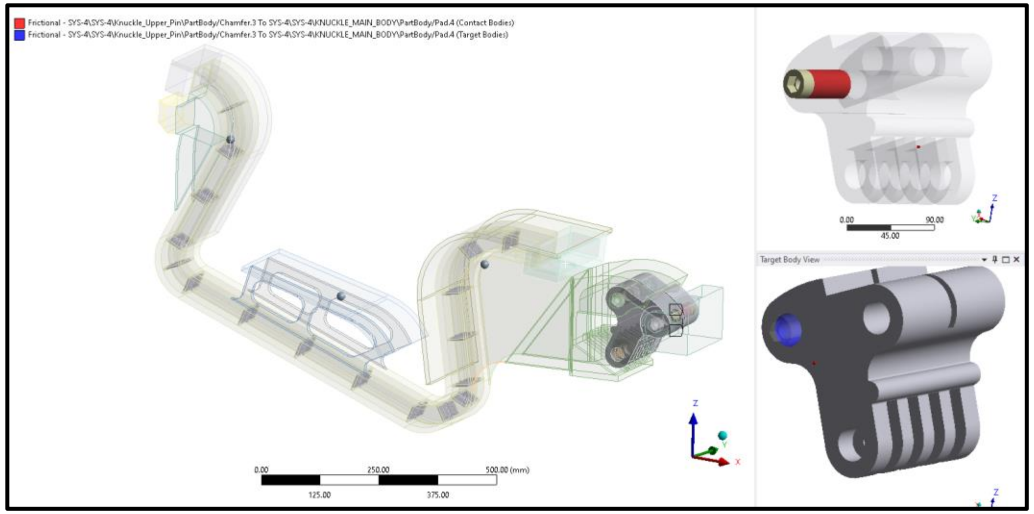


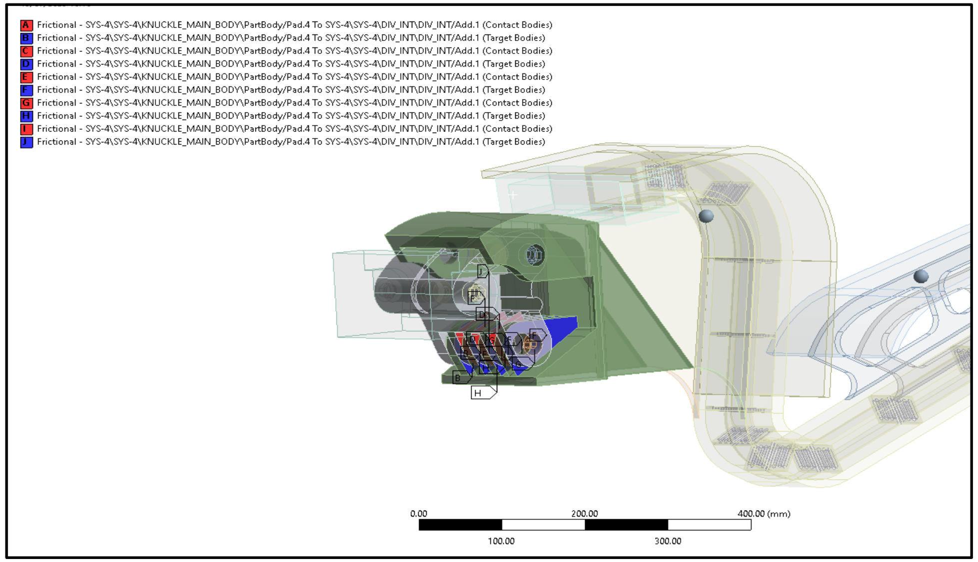
Knuckle, Shafts and Outboard Rail have been meshed using Hex. Elements, to minimize contact issues.

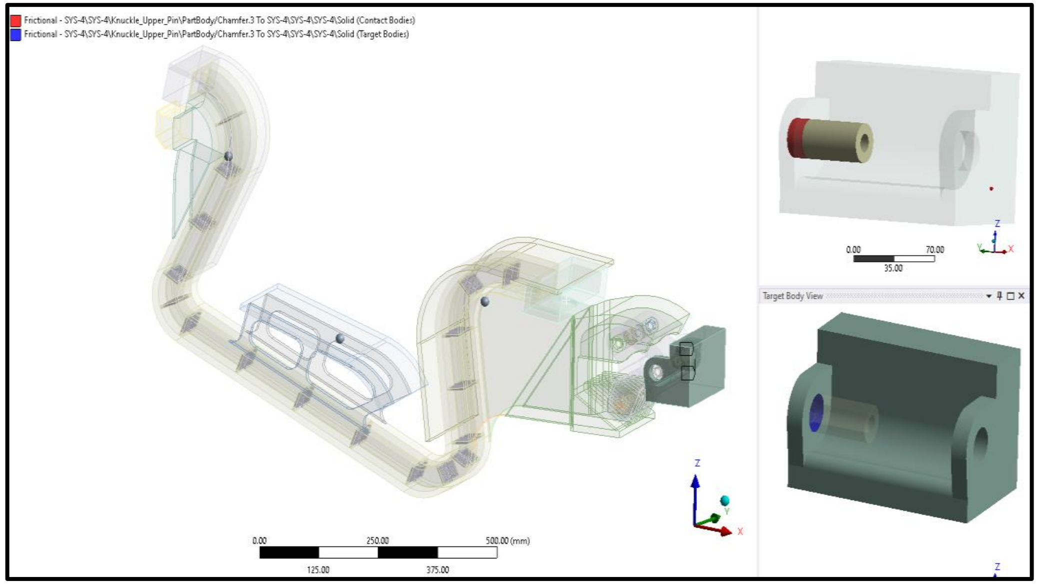
Global FE Model: Connections

Non-linear frictional contacts are set between sliding surfaces – **friction coefficient: 0.2**



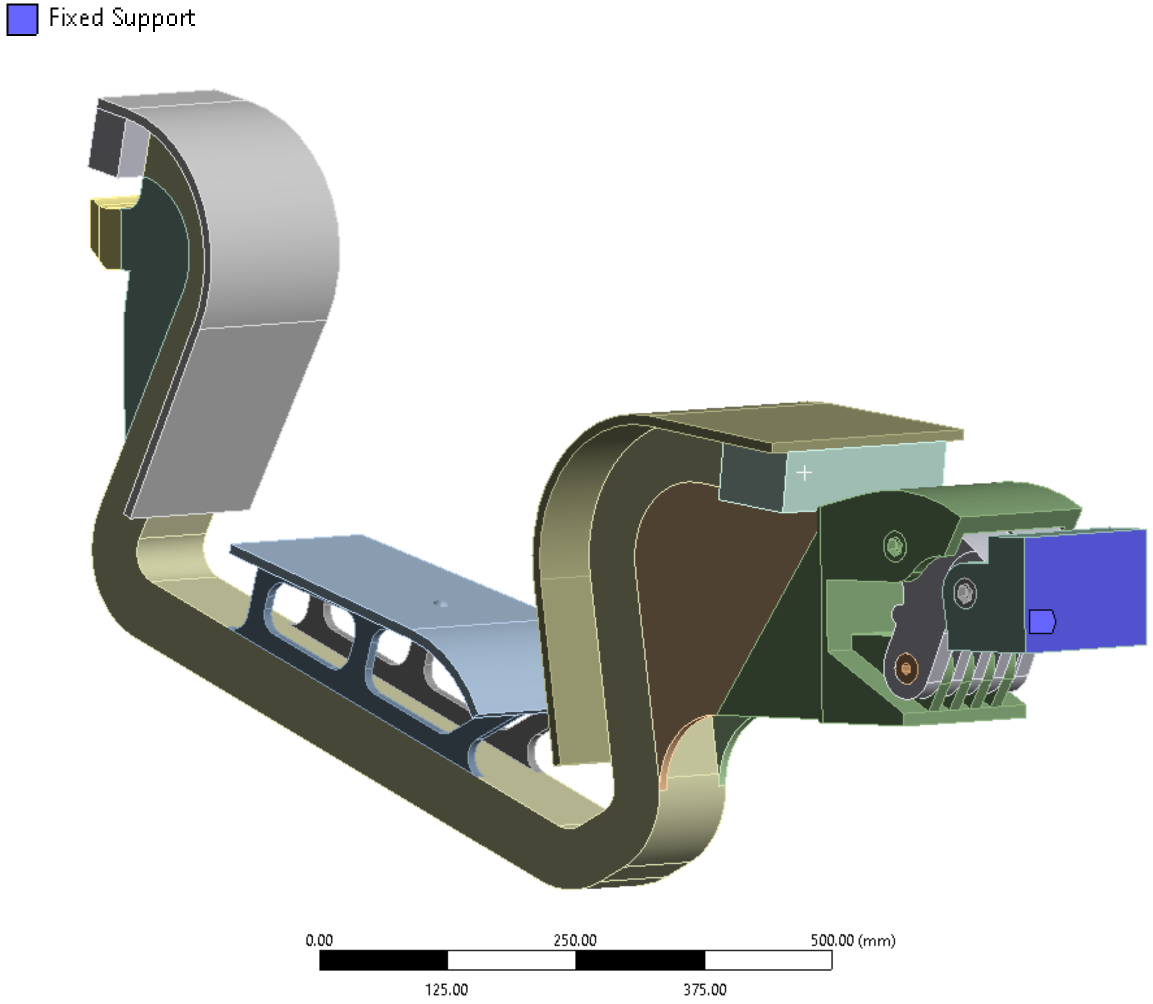




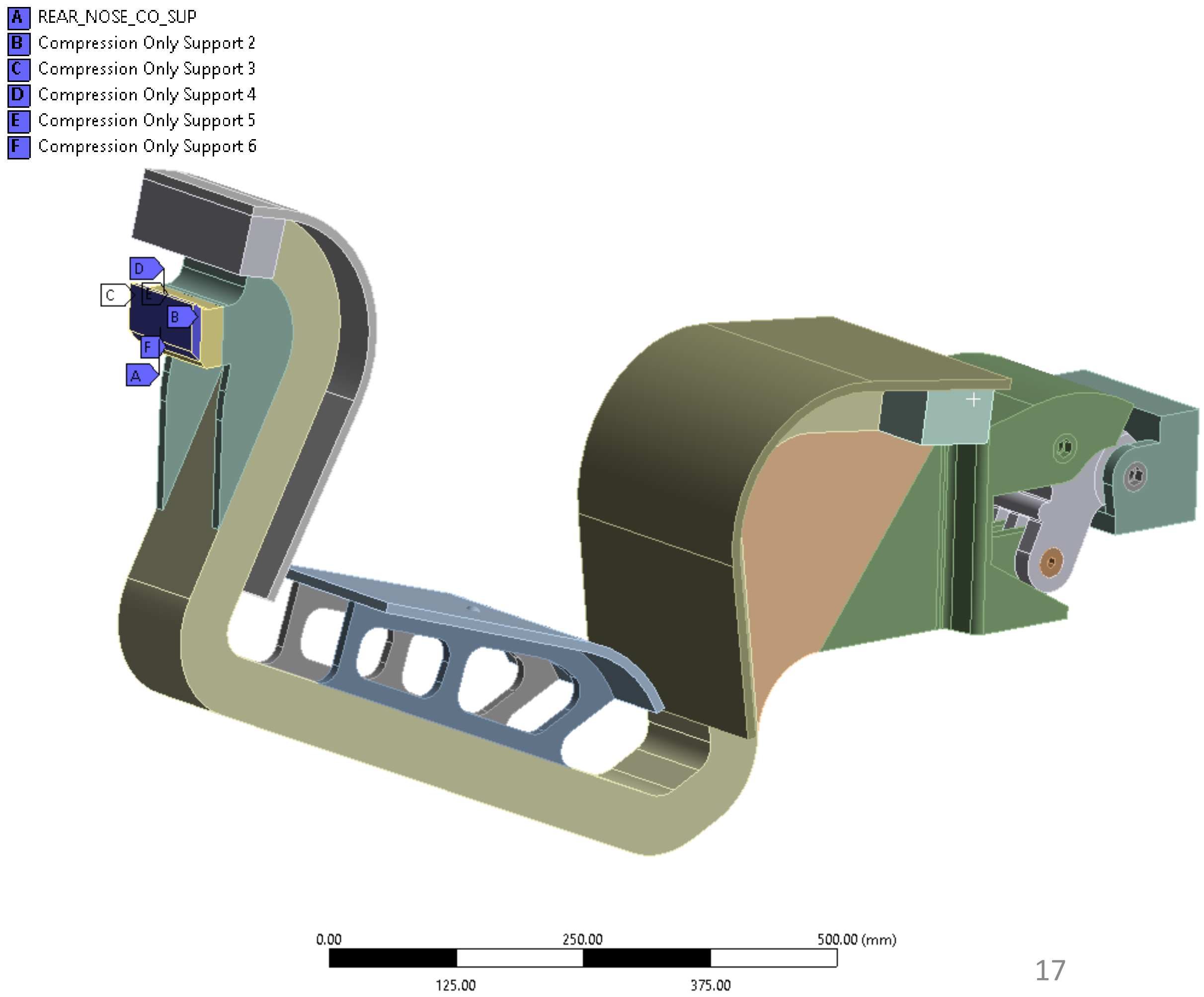


Global FE Model: Boundary Conditions

- ***Fixed Support set on the outer surface of the Outboard Rail***



- ***Compression Only Support set on the surfaces of the nose interfaced with the Inboard Rail (<u>the frictional interaction between Nose and Inboard rail has been neglected</u>)***

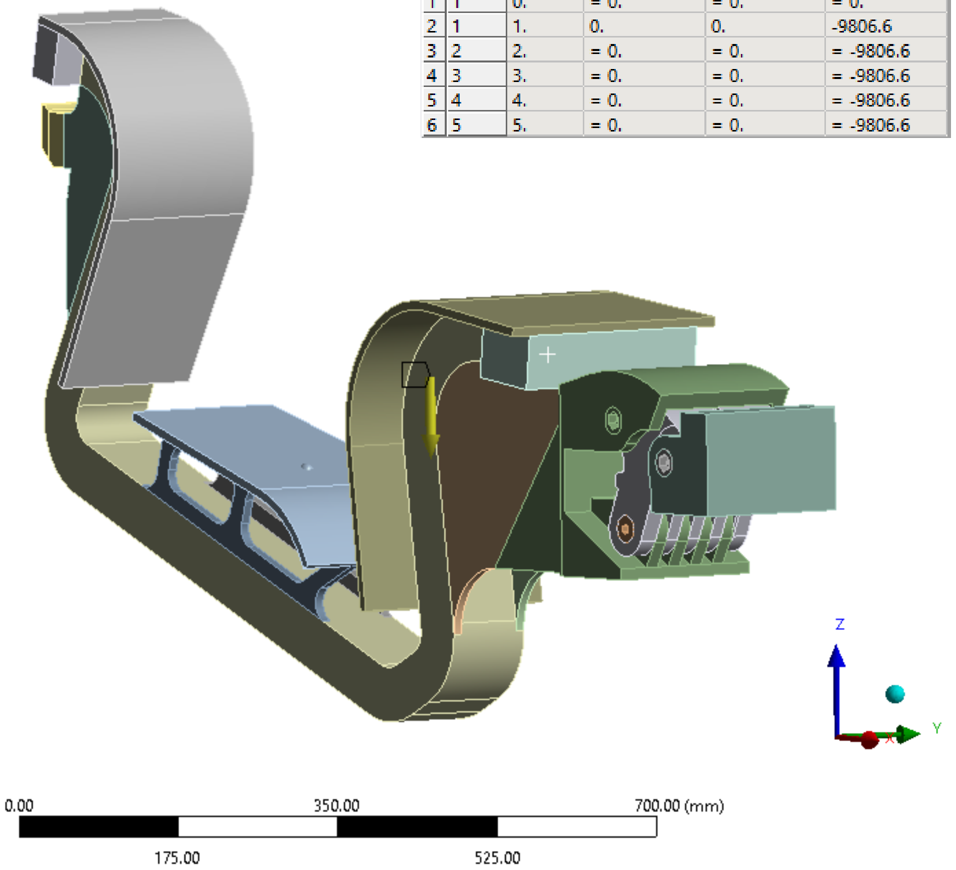


Global FE Model: Loads

The analisys has been carried out as **Multistep.**

STEP 1-Dead Weight

	Steps	Time [s]	X [mm/s²]	Y [mm/s²]	Z [mm/s²]
1	1	0.	= 0.	= 0.	= 0.
2	1	1.	0.	0.	-9806.6
3	2	2.	= 0.	= 0.	= -9806.6
4	3	3.	= 0.	= 0.	= -9806.6
5	4	4.	= 0.	= 0.	= -9806.6
6	5	5.	= 0.	= 0.	= -9806.6



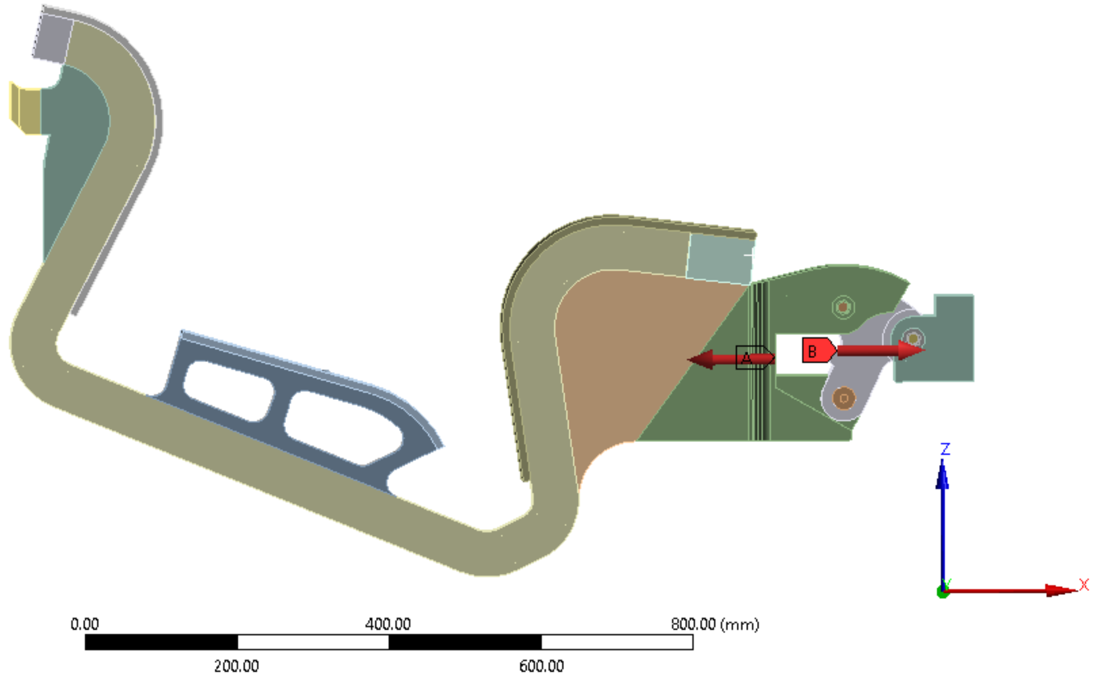
STEP 2-Preload (4 kN)

A Force: 4000. N

	Steps	Time [s]	X [N]	Y [N]	Z [N]
1	1	0.	0.	= 0.	= 0.
2	1	1.	0.	0.	0.
3	2	2.	-4000.	= 0.	= 0.
4	3	3.	= -4000.	= 0.	= 0.
5	4	4.	= -4000.	= 0.	= 0.
6	5	5.	= -4000.	= 0.	= 0.
*					

B Force 2: 4000. N

	Steps	Time [s]	X [N]	Y [N]	Z [N]
1	1	0.	0.	= 0.	= 0.
2	1	1.	0.	0.	0.
3	2	2.	4000.	= 0.	= 0.
4	3	3.	= 4000.	= 0.	= 0.
5	4	4.	= 4000.	= 0.	= 0.
6	5	5.	= 4000.	= 0.	= 0.
*					



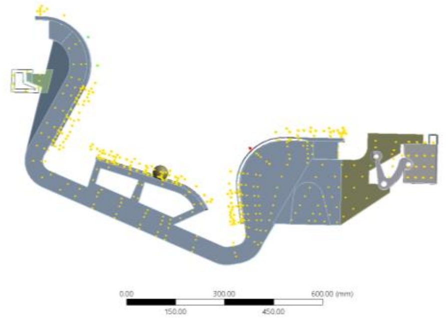
Global FE Model: Loads

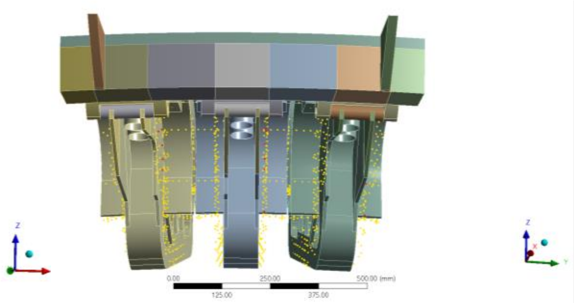
Elemental_data_DIV - > set of distributed force densities sent by LT Calcoli on July 2022

VDE_DW_fast
VDE_DW_slow

Calculated on div geometry included in

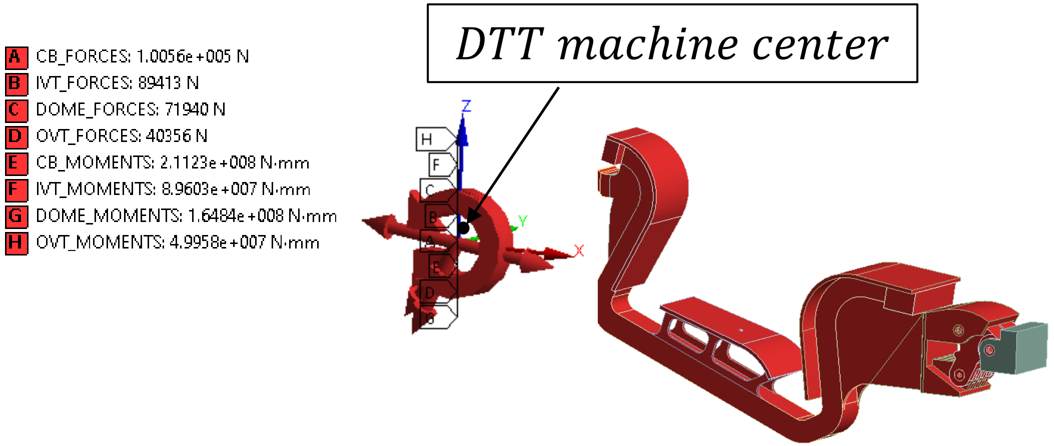
[DTT-R14_8R219_20220930_DTT2019_00191.zip]





STEP (3-4)-DVDE SLOW EM resultants of forces and moments

A remote point has been placed in DTT machine center and referred to the Cassette Body. The forces and moments have been applied in such remote point (their components have been specified in a proper oriented Coordinate System, with origin in the machine center ,the X axis along the radial direction, Y along toroidal, Z along vertical). The same has been done for the IVT, DOME, OVT support surfaces.



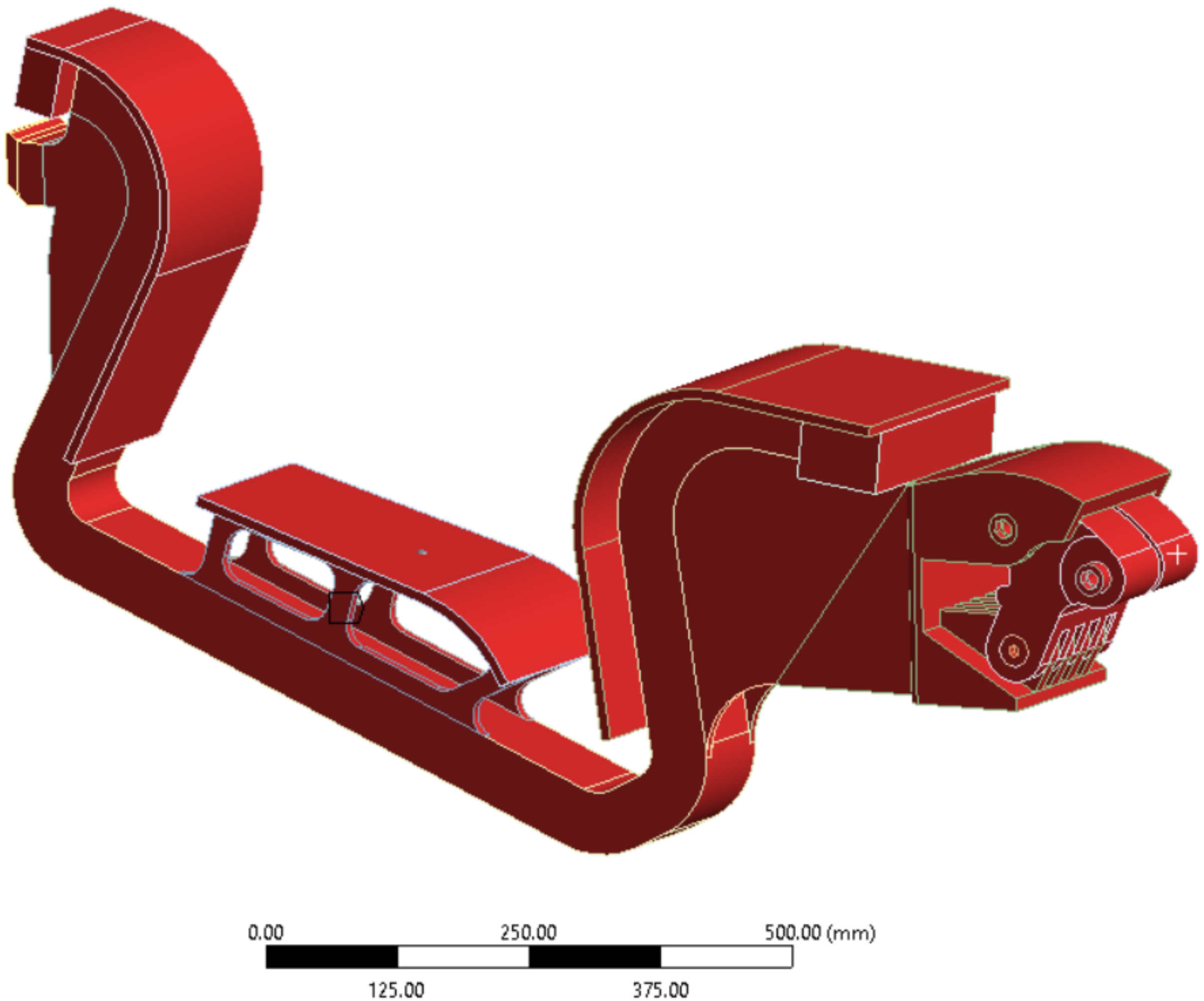
	F_x (N)	F_y (N)	F_z (N)	F_{tot} (N)	M_x (N mm)	M_y (N mm)	M_z (N mm)	M_{tot} (N mm)
CB	-61800	19100	-77000	$1{,}5 * 10^5$	$5{,}45 * 10^7$	$2{,}04 * 10^8$	$5{,}34 * 10^6$	$2{,}11 * 10^8$
OVT	40032	$792{,}7$	$-5041{,}5$	40356	$4{,}41 * 10^5$	$-4.99 * 10^7$	$1{,}37 * 10^6$	$4{,}99 * 10^7$
IVT	-88857	$-464{,}2$	$9940{,}8$	89431	$-6{,}21 * 10^4$	$8{,}96 * 10^7$	$-3{,}49 * 10^5$	$8{,}96 * 10^7$
$DOME$	-31585	$98{,}4$	-64636	71940	$-6{,}33 * 10^5$	$1{,}65 * 10^8$	$1{,}42 * 10^4$	$1{,}6485 * 10^8$

Global FE Model: Loads

Step 5-Thermal Condition

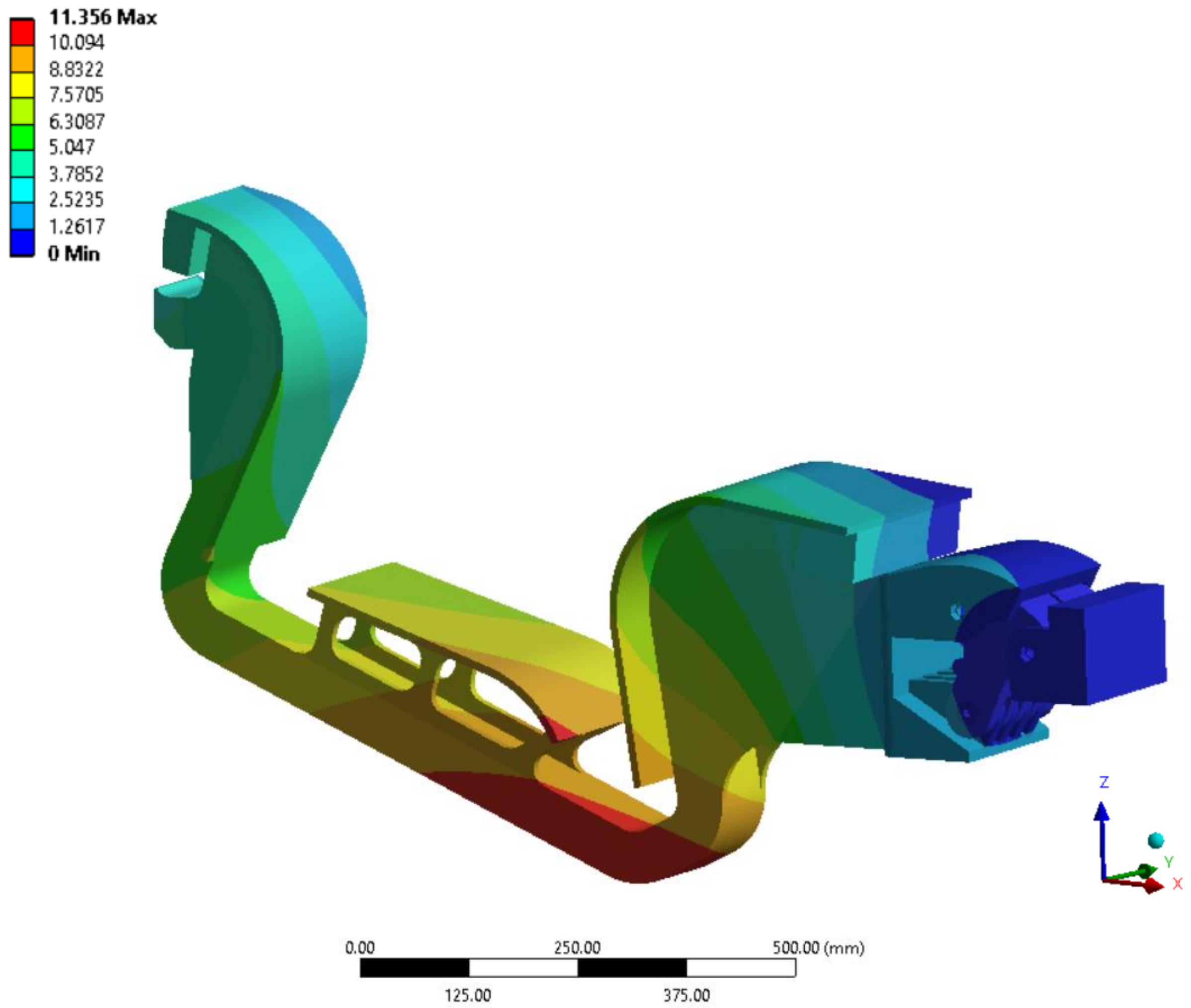
A uniform temperature of 130°C has been set on the Cassette Body

Steps	Time [s]	Temperature [°C]
1	0.	22.
1	1.	22.
2	2.	22.
3	3.	22.
4	4.	22.
5	5.	130.

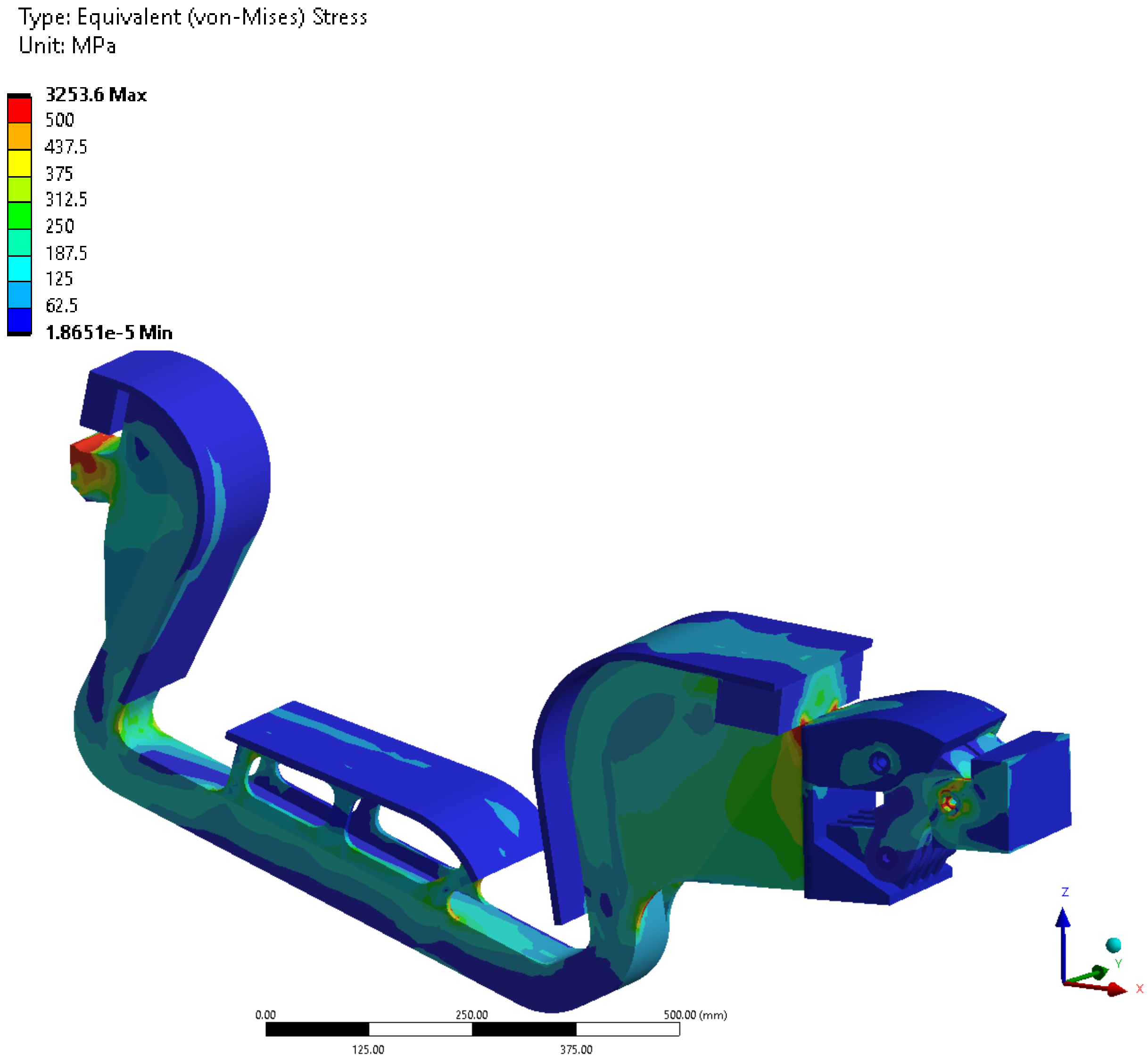


Global FE Model: Results

Total Displacement



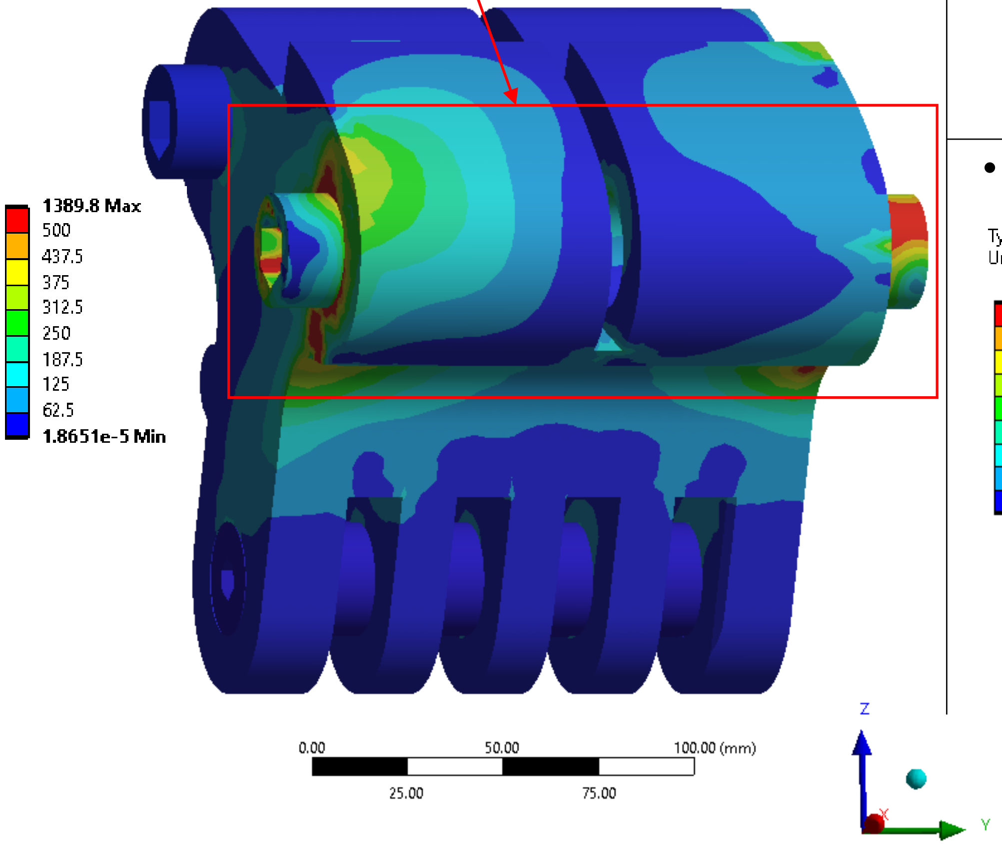
Eq. Von Mises Stress



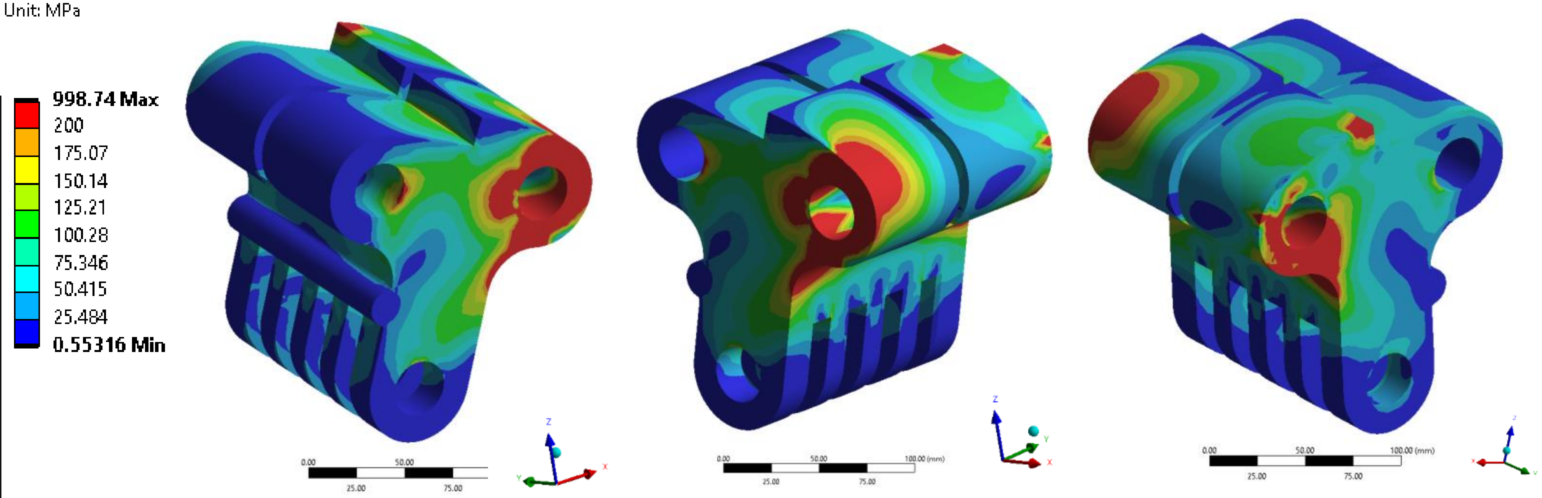
Global FE Model: Results

The Front Upper Shafts and the Front region of Knuckle Main Body are the most burdened. Therefore further investigation have been done in their nearby.

Type: Equivalent (von-Mises) Stress
Unit: MPa

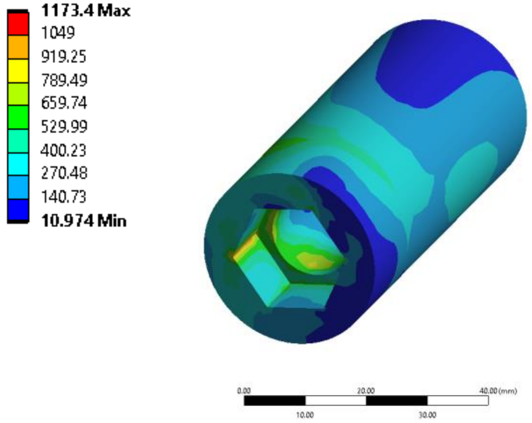


Type: Equivalent (von-Mises) Stress
Unit: MPa



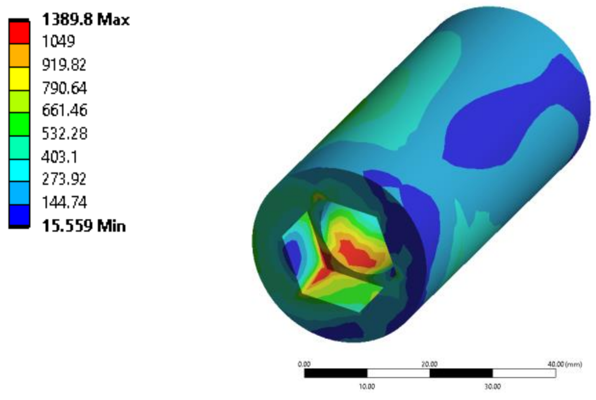
- Left Shaft

Type: Equivalent (von-Mises) Stress
Unit: MPa



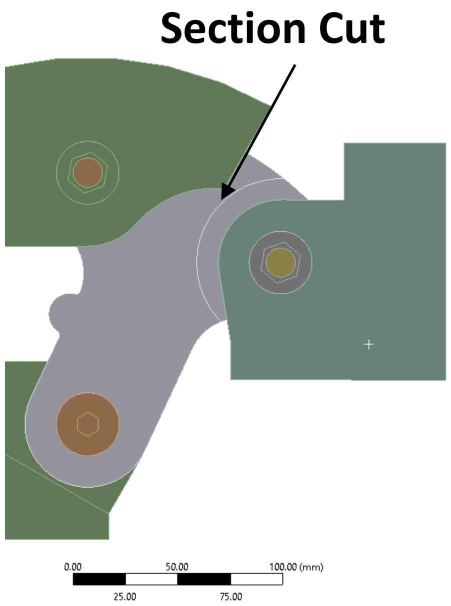
- Right Shaft

Type: Equivalent (von-Mises) Stress
Unit: MPa

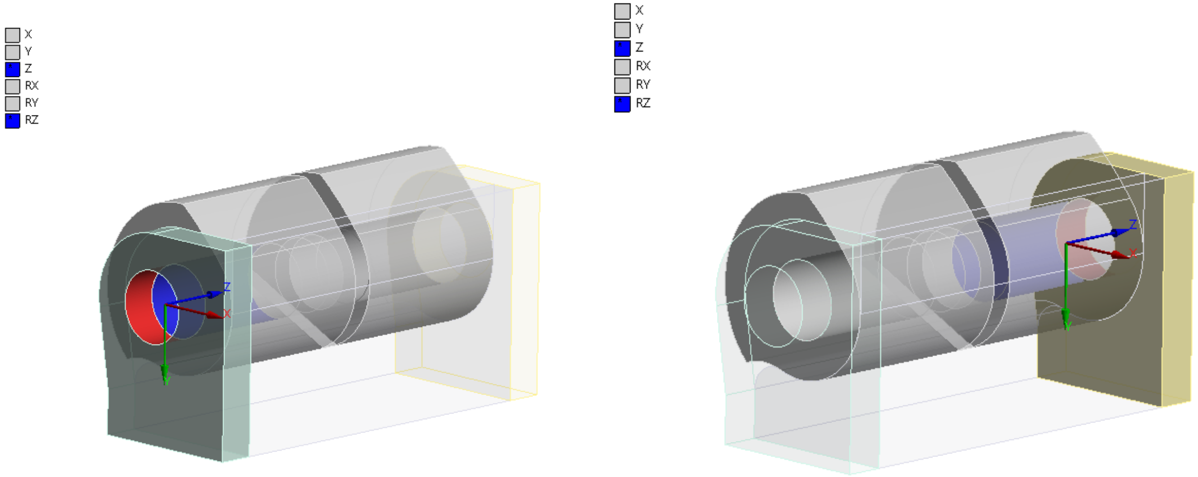


Submodel 1-Cylindrical joints: Model building

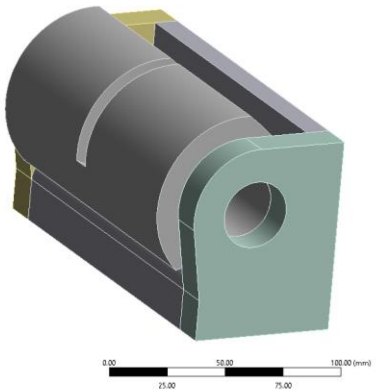
The nearby of the region highlighted in the previous slide have been submodeled. The idea is to cut the Knuckle Main Body , as close as possible to the outer part of the model, to minimize lost of load informations. The Front Upper Shafts have been removed and substituted with cylindrical joints, in order to evaluate the shear constraint reactions and perform a preliminary hand calculation on the the Shafts. **The other imposed contacts stay the same.**



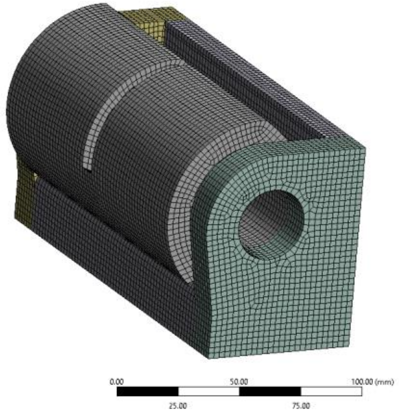
- Cylindrical joints



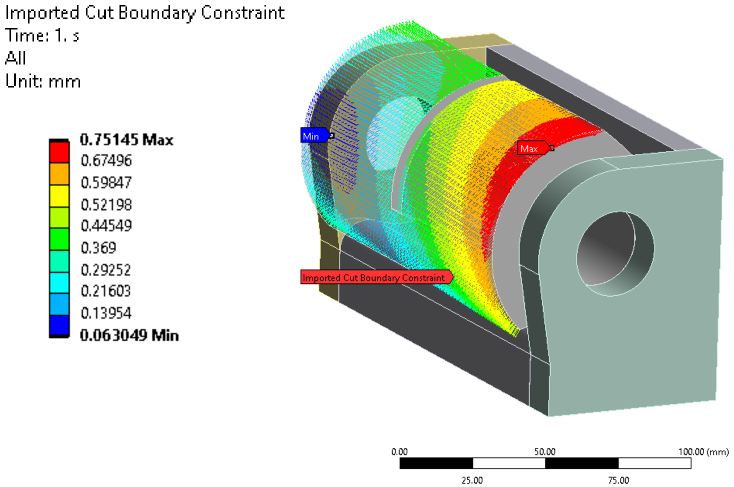
- Geometry



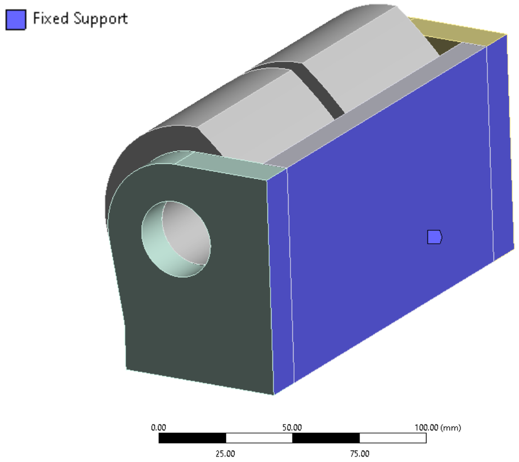
- Mesh



- Imported Displacement Field on the section cut

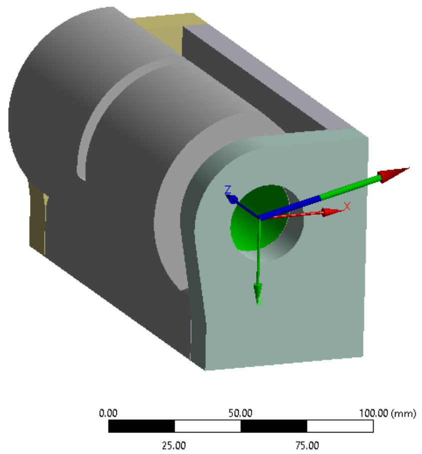


- Fixed Support



Submodel 1-Cylindrical joints: Shafts Shear Stress Hand Calculations

	Time [s]	Joint Probe (Total Force X) [N]	Joint Probe (Total Force Y) [N]	Joint Probe (Total Force Z) [N]	Joint Probe (Total Force Total) [N]
1	1.	-1.9181e+005	5.8073e+005	0.	6.1159e+005



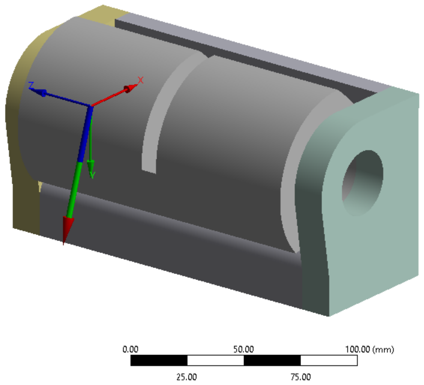
A brief hand calculation on the shear stress value has been performed for the Left Upper Shaft:

- *Upper shaft external Diameter*: $D = 30\ mm;$
- *Upper shaft internal Diameter*: $d = 14\ mm;$
- *Total shear force*: $T_{tot} = 6.1159 * 10^5 N;$

Shear Stress(in joint coordinate system XY plane):

$$\boldsymbol{\tau_{XY}} = \frac{\boldsymbol{T_{tot}}}{\boldsymbol{A}} = \frac{\boldsymbol{T_{tot}}}{\boldsymbol{\pi}\left(\left(\frac{\boldsymbol{D}}{2}\right)^2 - \left(\frac{\boldsymbol{d}}{2}\right)^2\right)} = \mathbf{1106}\ \boldsymbol{MPa}$$

	Time [s]	Joint Probe 2 (Total Force X) [N]	Joint Probe 2 (Total Force Y) [N]	Joint Probe 2 (Total Force Z) [N]	Joint Probe 2 (Total Force Total) [N]
1	1.	9.2815e+005	-2.2058e+005	0.	9.5401e+005



A brief hand calculation on the shear stress value has been performed for the Right Upper Shaft:

- *Upper shaft external Diameter*: $D = 30\ mm;$
- *Upper shaft internal Diameter*: $d = 14\ mm;$
- *Total shear force*: $T_{tot} = 9.5401 * 10^5 N;$

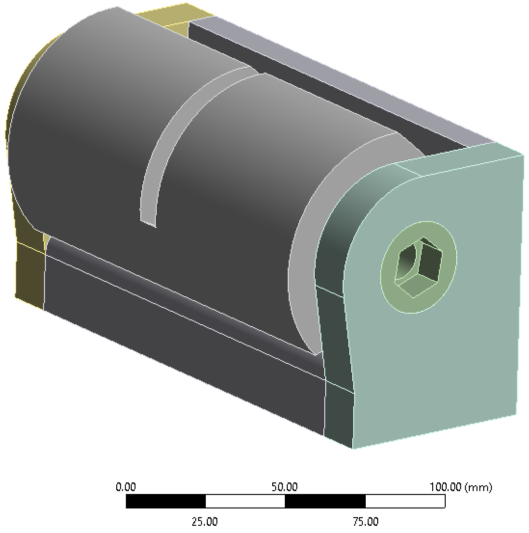
Shear Stress(in joint coordinate system XY plane):

$$\boldsymbol{\tau_{XY}} = \frac{\boldsymbol{T_{tot}}}{\boldsymbol{A}} = \frac{\boldsymbol{T_{tot}}}{\boldsymbol{\pi}\left(\left(\frac{\boldsymbol{D}}{2}\right)^2 - \left(\frac{\boldsymbol{d}}{2}\right)^2\right)} = \mathbf{1725}\ \boldsymbol{MPa}$$

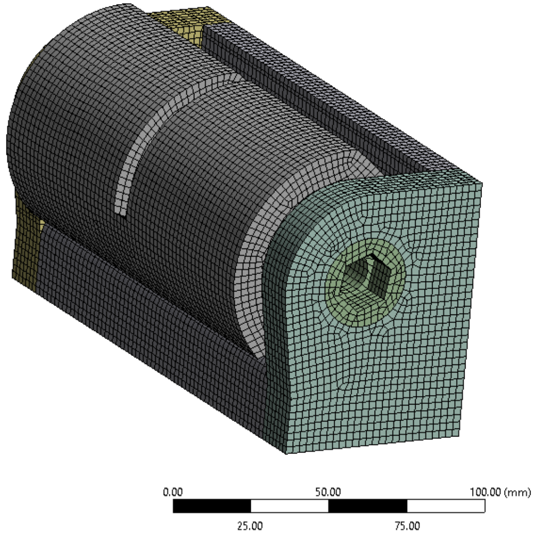
Submodel 2-Contacts: Model building

The purpose of the submodeling analysis conducted is to capture and evaluate the stress conditions present in the shafts and the front section of the knuckle with utmost precision. <u>All the submodeled components have been considered and the contact set is the same of the global model.</u>

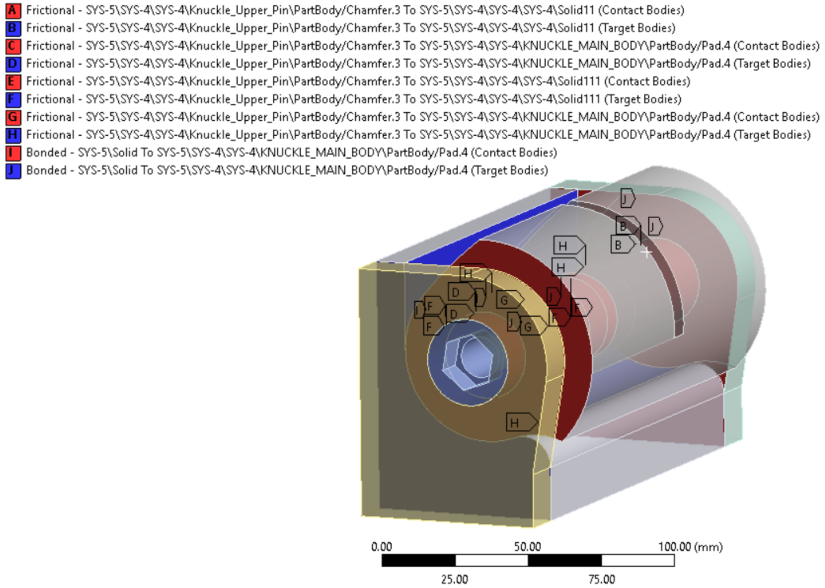
- Geometry



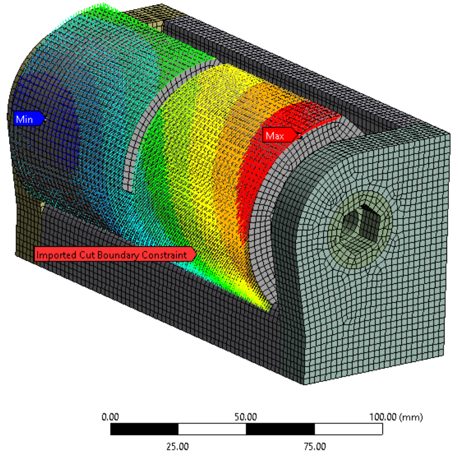
- Mesh



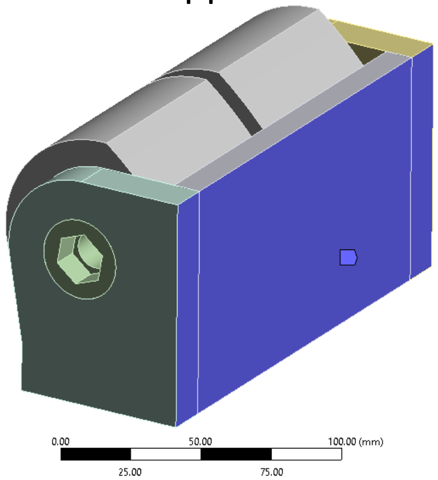
- Contacts



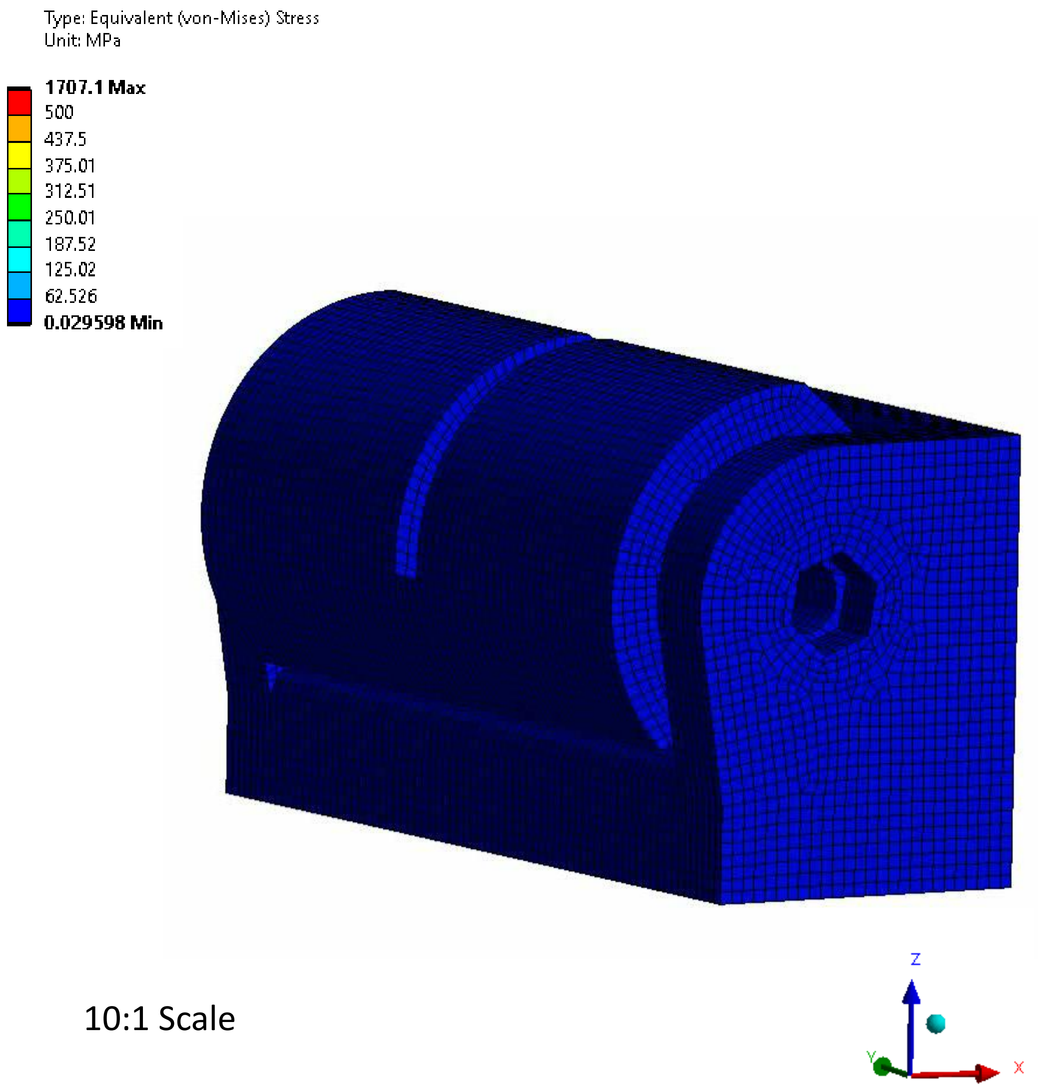
- Imported Displacement Field on the section cut



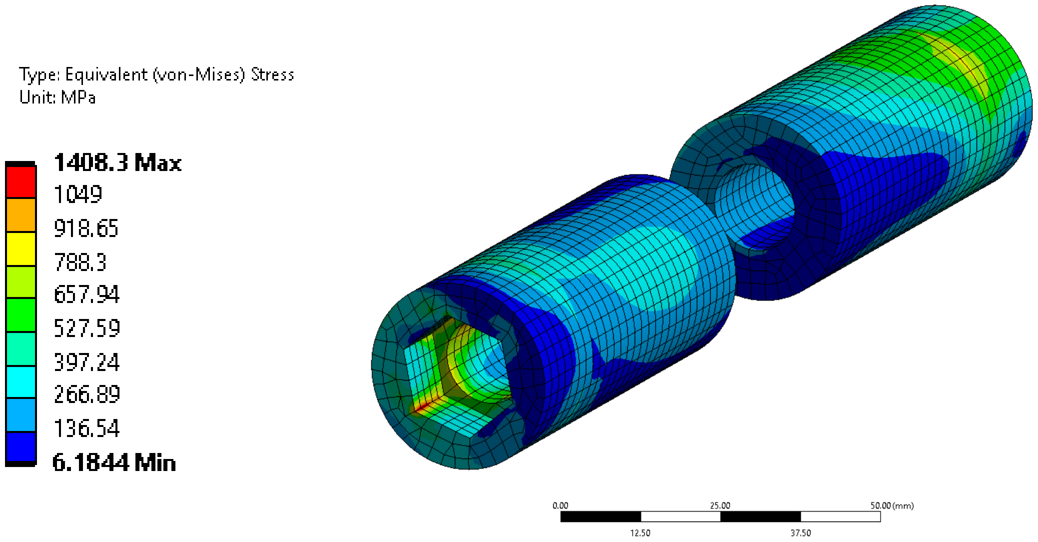
- Fixed support

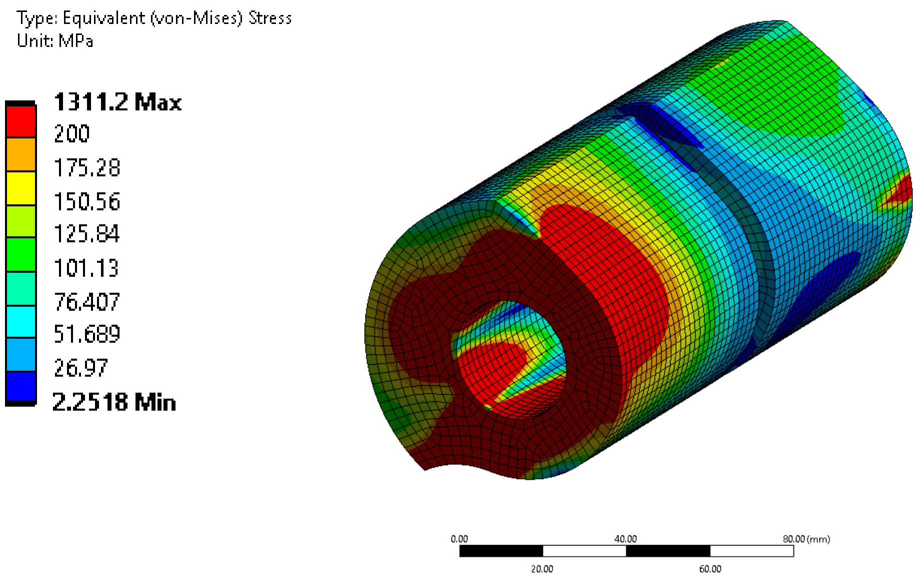


Submodel 2-Contacts: Results

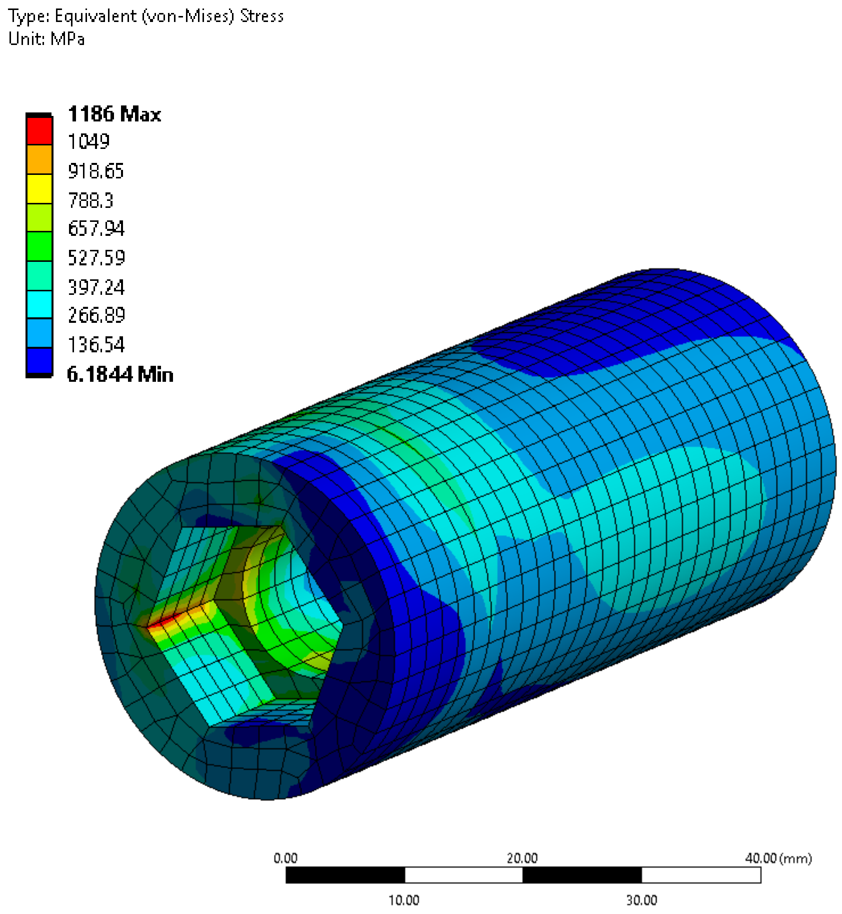


10:1 Scale



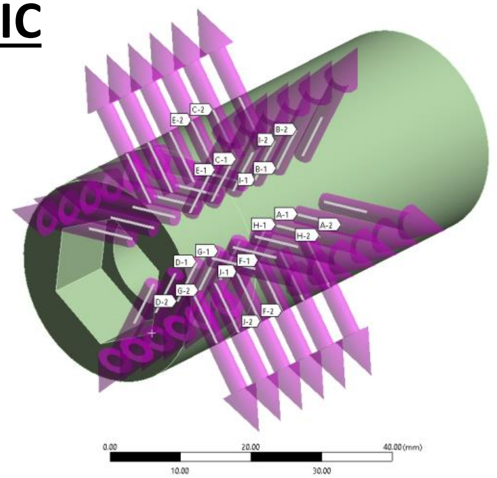


Submodel 2-Contacts: Left Upper Shaft Results



Rules applied for verification: <u>ITER SDC-IC</u>

Several paths have been probed, the SCL in the most critical one has been reported

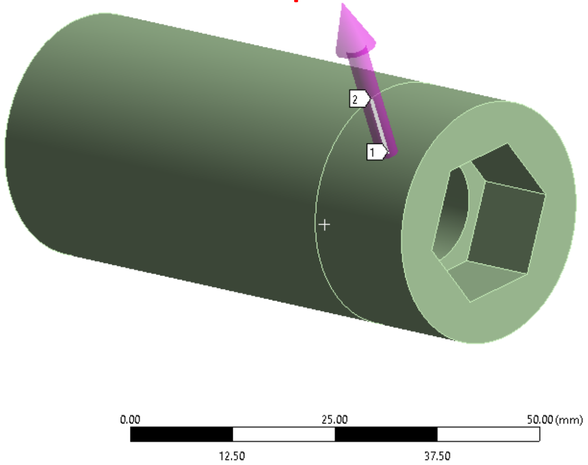


Point 1 on SCL

Linearized Eq. Von Mises Stress:

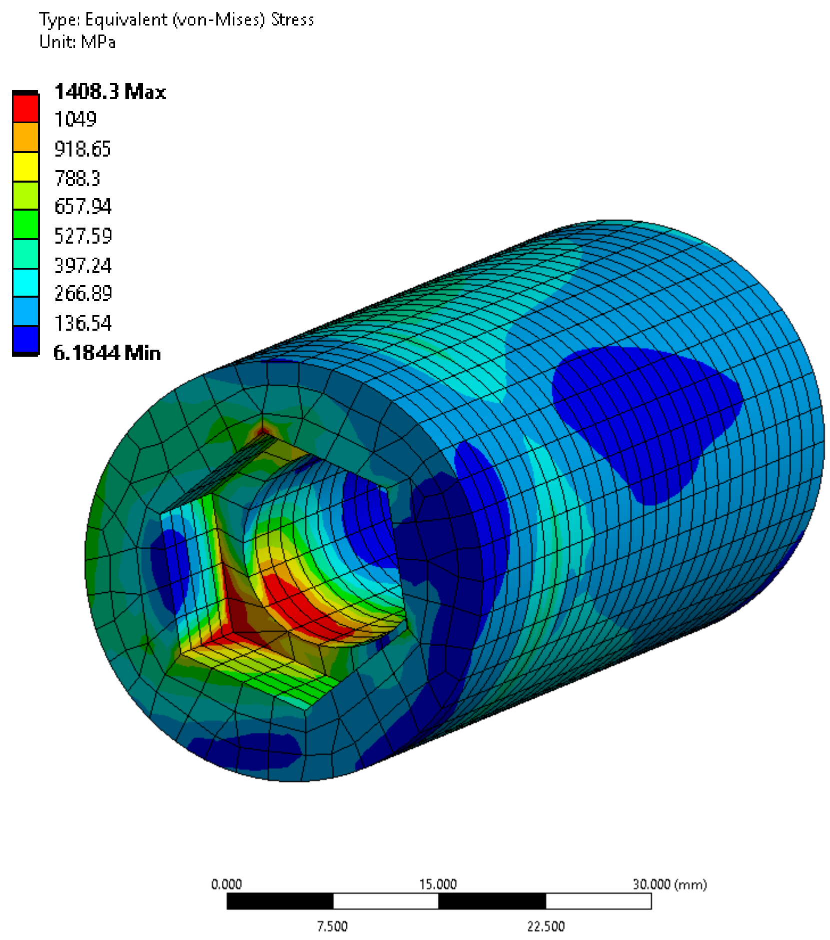
Pm=748 MPa > Sm=425 Mpa

Pm +Pb=931.35 Mpa > 1.5 Sm=637.5 MPa



The shaft (d_{ext} =30 mm) is not verified

Submodel 2-Contacts: Right Upper Shaft Results



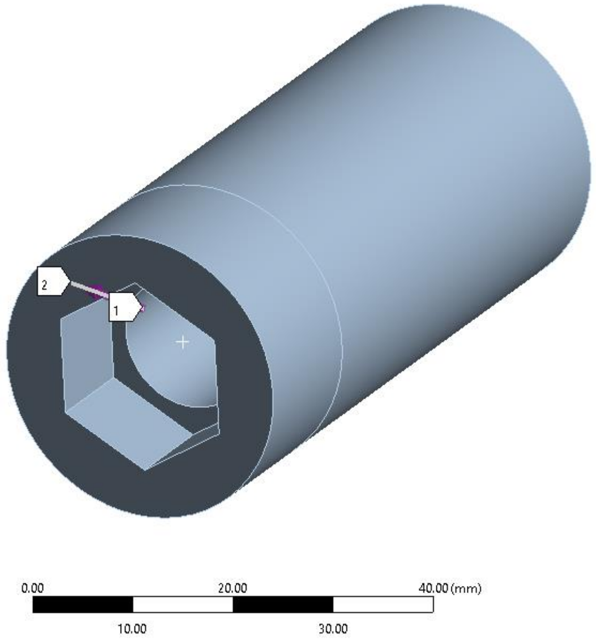
Point 1 on SCL

Linearized Eq. Von Mises Stress:

Pm=690.67> Sm=425 Mpa

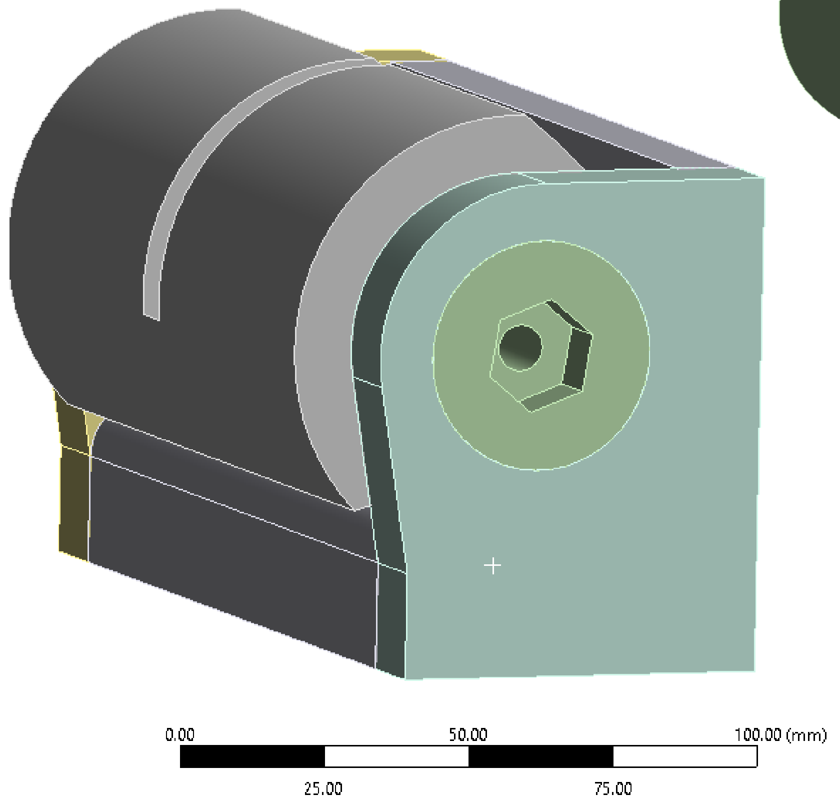
Pm +Pb=1134.12> 1.5 Sm=637.5 MPa

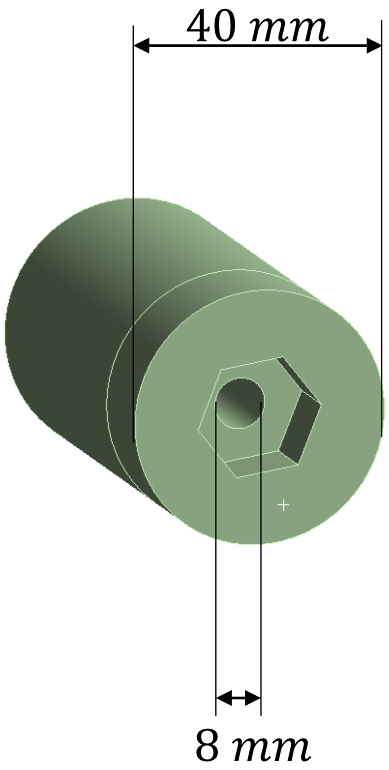
The shaft (d_{ext} =30 mm) is not verified



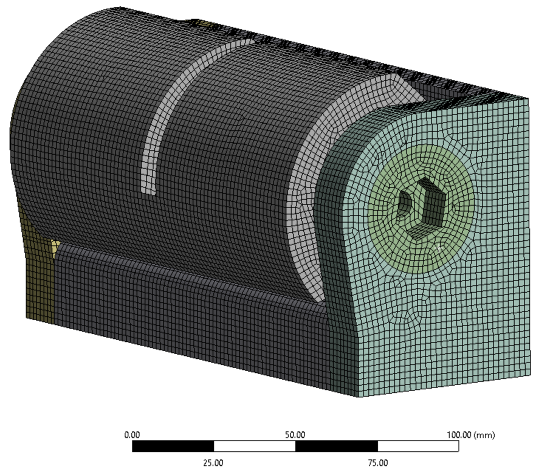
Submodel 3-Contacts: Model building

The external diameter and internal diameter of the shafts have been iteratively changed with the specific aim of ensuring compliance with the FEM verification, enabling successful validation.

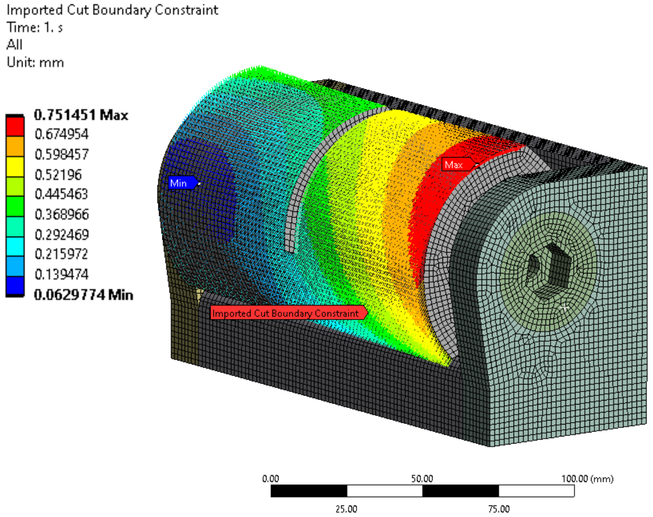




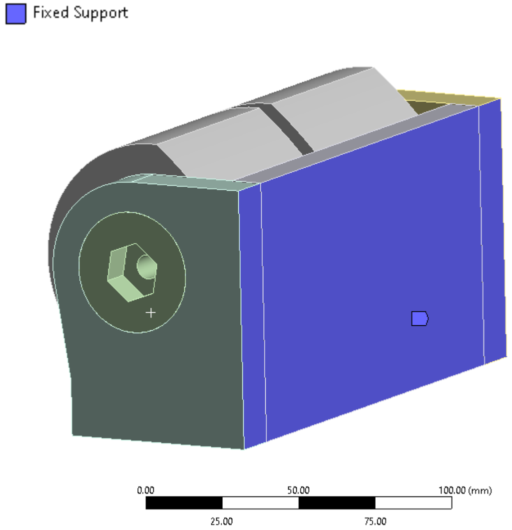
- Mesh



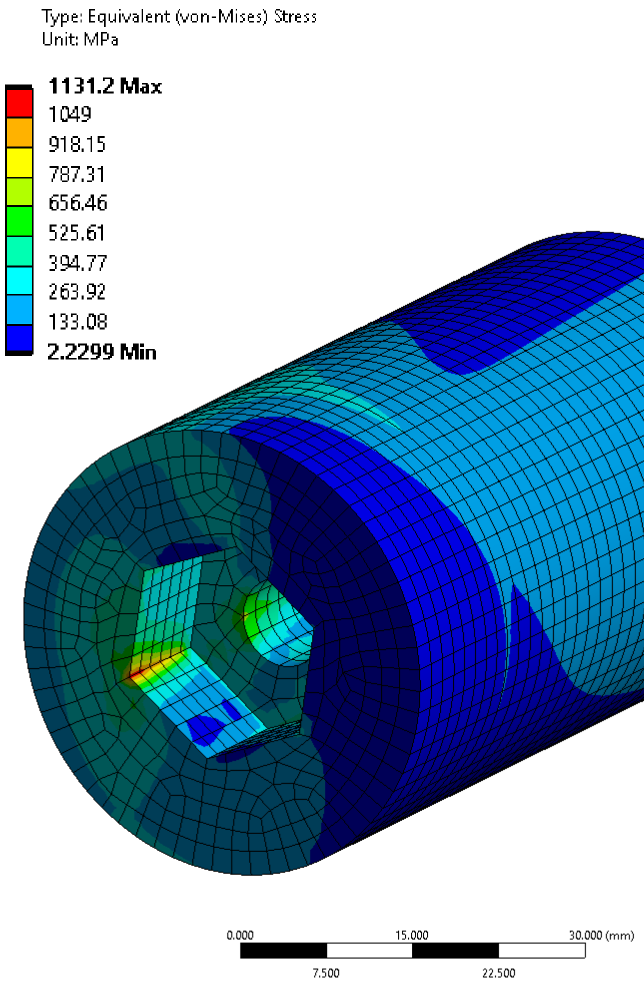
- Imported Displacement Field on the section cut



- Fixed support



Submodel 3-Contacts: Left Upper Shaft Results



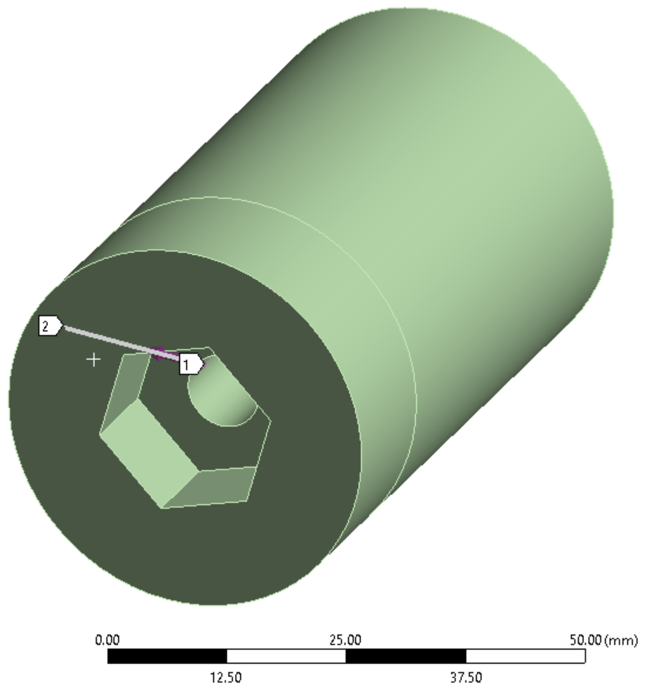
Point 2 on SCL

Linearized Eq. Von Mises Stress:

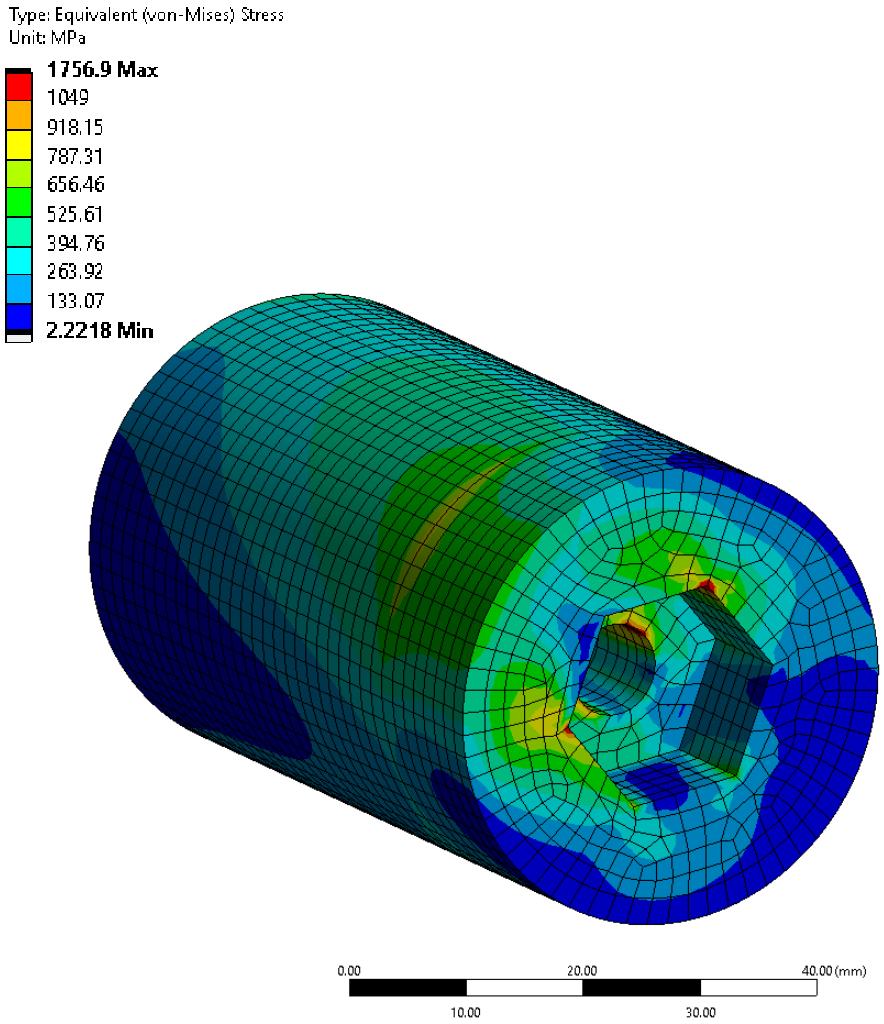
Pm=282.12 MPa < Sm=425 Mpa

Pm +Pb=345.83 MPa < 1.5 Sm=637.5 MPa

The shaft is verified



Submodel 3-Contacts: Right Upper Shaft Results

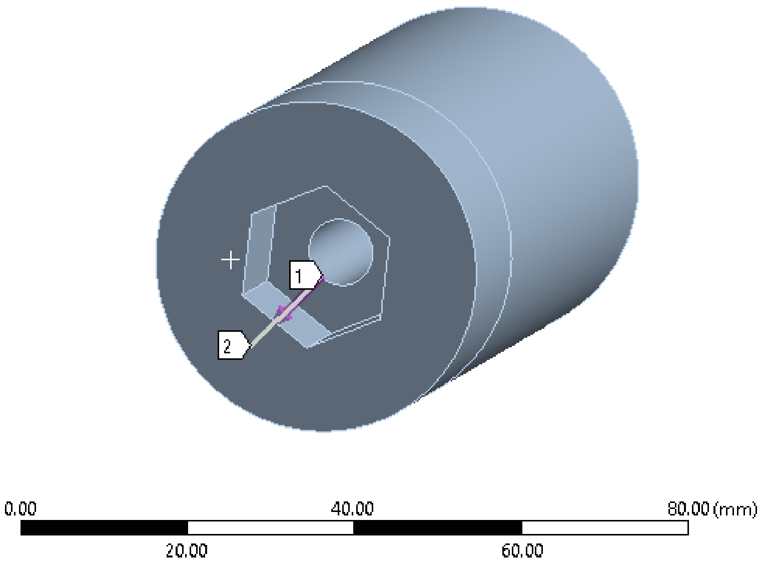


Point 1 on SCL

Linearized Eq. Von Mises Stress: Pm=380.56 MPa < Sm=425 Mpa

Pm +Pb=533.47 MPa < 1.5 Sm=637.5 MPa

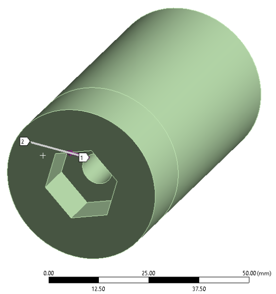
The shaft is verified



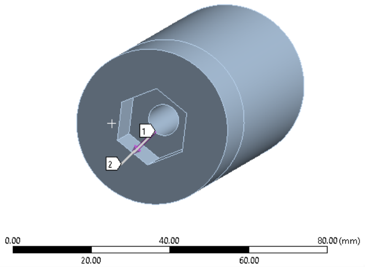
Submodel 3-Contacts: Result summary

Component	Location	SCL Results	Safety Factor
Left Up. Shaft	2	Pm=282.12MPa	**1.51**
		Pm+Pb=345.83 MPa	**1.84**
Right Up. Shaft	1	Pm=380.56 MPa	**1.12**
		Pm+Pb=533.47 MPa	1.2
Knuckle Main Body	2	Pm=398.53 MPa	**-**
		Pm+Pb=717.35 MPa	**-**

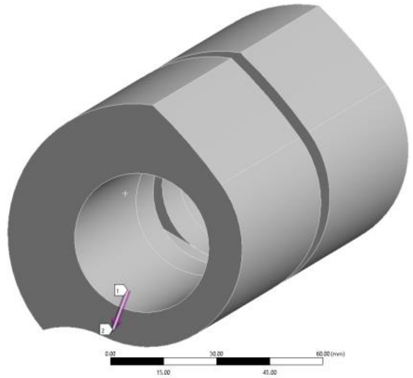
Left Up. Shaft



Right Up. Shaft



Knuckle Main Body



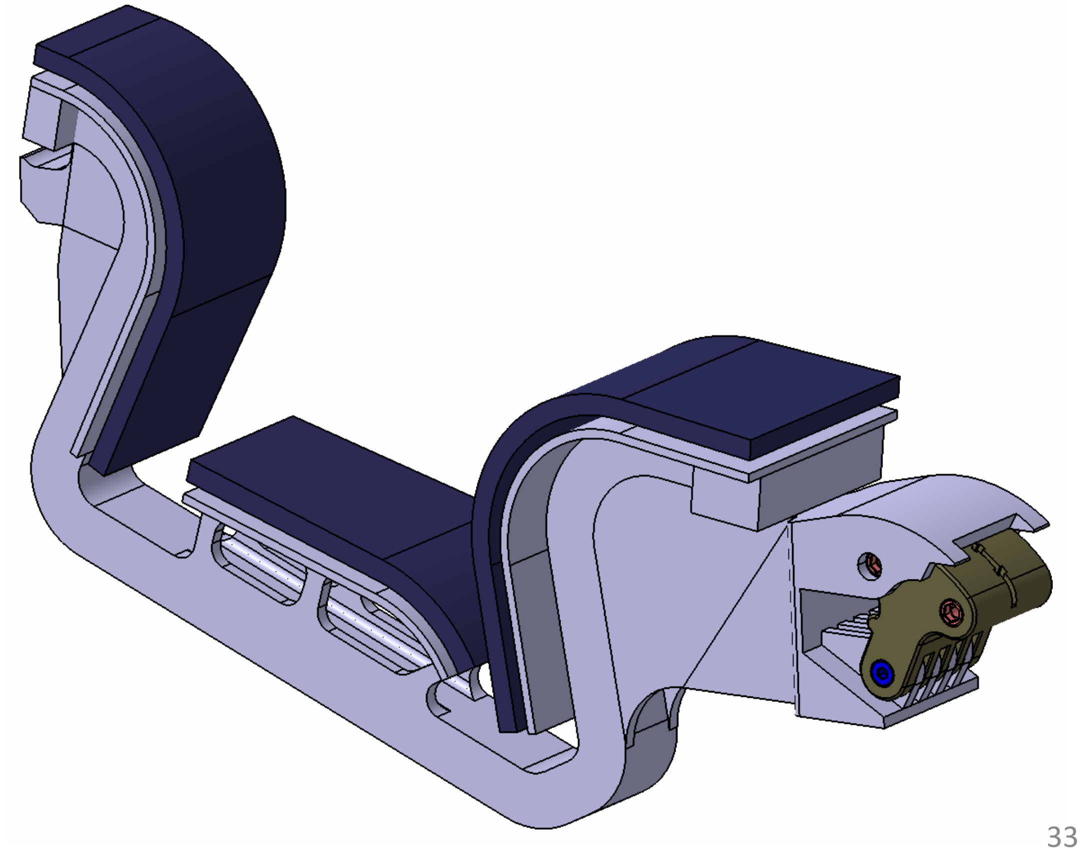
Further improvements have to be done to strenghten the Knuckle Main Body design

Conclusions

- The Shafts geometry has been optimized in compliance with the available load configuration.

- Knuckle Main Body to be optimized in the area of the pin shafts .

The Cassette Body-Locking System CAD model is now detailed enough to proceed to the EM calculations.
Once the new EM loads will be evaluated as elemental force densities, the structural analysis will be done again.



Thanks for your attention!