CA3ViAR

Dissemination Event #1: Design of a Composite UHBR Fan

Stress and Fatigue Analysis

05th September 2022

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Introduction

Stress analysis have been conducted on all the new test article parts designed by CA3ViAR.

For composite parts, the material has been characterized experimentally to reduce the level of conservatism and increase the accuracy of the structural design, in order to preserve the achievement of the project objective of going close to instabilities during WT operations.

The following subsections present the experimental campaign to characterize the composite material and all the analyses performed to validate the structural design of blade and metallic parts.

Agenda

Material Characterization

MTC510

- Epoxy resin system reinforced with carbon fibres designed to cure between 80°C and 120°C allowing flexibility in component manufacture
- Can be supplied on a variety of fabrics and in UD format to meet many different cost and manufacturing requirements.

<u>The basic features are:</u>

- Cure temperature from 80°C to 120°C
- Service temperature up to 135°C after post cure
- Low CTE and shrinkage
- Work life at 20°C: 30 days
- Storage life at -18°C: 12 months
- Very low VOC content – no added solvents during manufacture
- Excellent surface finish

Agenda

CA3ViAR Dissemination Event #1 - Stress and Fatigue Analysis

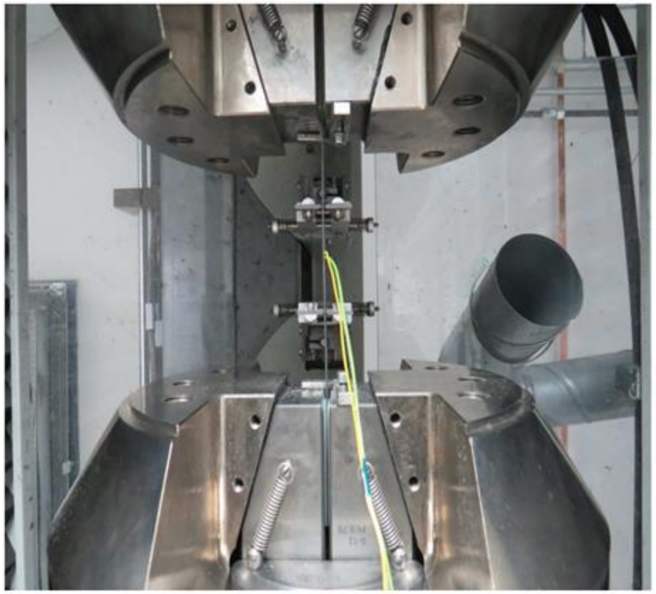
Material Characterization

Mechanical Tests

Following the ASTM D3039 (Ambient Temperature) tests were set up, measuring the most important properties for FEA-models:

- Tensile strength 0º and 90º (MPA)
- Tensile modulus of Elasticity 0º and 90º (MPA)
- Poisson ratio
- Tensile strain 0º and 90º (%)
- Density (kg/m^3)

➢ Mitigate the risk of performing a blade design by relying on insufficiently realistic nominal material properties (datasheet)



CFRP specimen under tensile load application

Main outcome:

The tensile strength in direction 2 (perpendicular to fibres' direction) is 30 MPa.
It is much lower than the manufacturer's datasheet (54 MPa).
This difference is referred to the change of the manufacturing process (closed mould/vacuum).

fibers dir 11 — specimen testing

Legende	Nr	Specimen	h (mm)	w (mm)	L (mm)	P^{max} (N)	E^{chord} (MPa)	F^{tu} (MPa)	ε^{tu} (%)	ν
	max			15,20	250					
	min			14,80	---					
	1	P50-CM-003-1_1	1,25	14,97	250	39085	109155	2097	1,975	0,301
	2	P50-CM-003-1_2	1,28	15,01	250	39137	100844	2041	2,085	0,293
	3	P50-CM-003-1_3	1,30	15,02	250	44287	107620	2275	2,202	0,320
	4	P50-CM-003-1_4	1,32	15,03	250	45458	109165	2298	2,156	0,308
	5	P50-CM-003-1_5	1,32	14,98	250	43639	104121	2211	2,238	0,235

fibers dir 11 — statistical analysis for 5 specimen

Serie n = 5	h (mm)	w (mm)	P^{max} (N)	E^{chord} (MPa)	F^{tu} (MPa)	ε^{tu} (%)	ν
$\bar{x}$	1,29	15,00	42321	106181	2184	2,131	0,292
min	1,25	14,97	39085	100844	2041	1,975	0,235
max	1,32	15,03	45458	109165	2298	2,238	0,320
R	0,07	0,07	6373	8321	256,5	0,2633	0,085
s	0,03	0,03	3002	3624	111,8	0,1044	0,033
ν [%]	2,33	0,19	7,09	3,41	5,12	4,90	11,40

fibers dir 22 — specimen testing

Legende	Nr	Specimen	h (mm)	w (mm)	L (mm)	P^{max} (N)	E^{chord} (MPa)	F^{tu} (MPa)	ε^{tu} (%)	ν
	max			25,20	226					
	min			24,80	---					
	1	P50-CM-004-1_1	2,24	25,07	225	1935	6992	34,48	0,4788	0,022
	2	P50-CM-004-1_2	2,29	25,01	225	1688	6727	29,5	0,4216	0,022
	3	P50-CM-004-1_3	2,32	24,91	225	1489	6655	25,8	0,3699	0,026
	4	P50-CM-004-1_4	2,31	25,02	225	1684	6594	29,08	0,4224	0,021
	5	P50-CM-004-1_5	2,29	25,03	225	1852	6777	32,32	0,4647	0,022

fibers dir 22 — statistical analysis for 5 specimen

Serie n = 5	h (mm)	w (mm)	P^{max} (N)	E^{chord} (MPa)	F^{tu} (MPa)	ε^{tu} (%)	ν
$\bar{x}$	2,29	25,01	1730	6749	30,24	0,4315	0,023
min	2,24	24,91	1489	6594	25,8	0,3699	0,021
max	2,32	25,07	1935	6992	34,48	0,4788	0,026
R	0,08	0,16	446	398	8,685	0,1089	0,005
s	0,03	0,06	172,4	152,7	3,315	0,04276	0,002
ν [%]	1,39	0,24	9,97	2,26	10,96	9,91	8,67

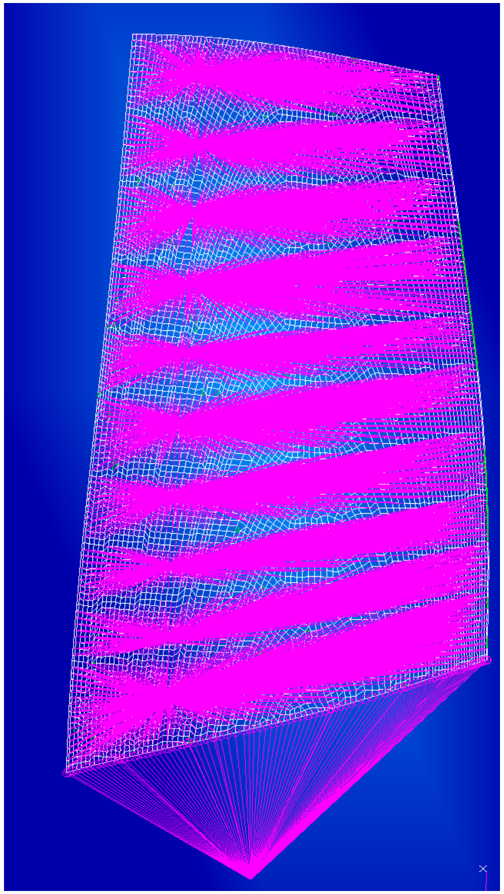
Agenda

Stress Analysis of Composite Blade & Fatigue

Blade Stress Analysis

Mesh

The base for the stress analysis on CA3ViAR blade is a model with a mesh of approximately 14K elements, which guarantees a good compromise between accuracy and computation time.



Boundary conditions and loading

- The blade is constrained at the blade root using an RBE2 MPC
- The load is distributed stripewise along the blade span by a set of 10 RBE3 (rigid body elements)
- each RBE corresponds to an aerodynamic load (Fx, Fy, Fz, Mx, My, Mz)
- Furthermore rotational forces are applied to the rotational axis
- A knockdown factor 1.3 times a safety factor of 2.5 is used on the material allowables
- The Tsai-Wu criterion is used to analyse strenght of the blade
- geometric non-linear calculation: Nastran SOL106

Agenda

1. **Introduction**
2. **Stress and Fatigue Analysis**
    1. Material Characterization
    2. Stress Analysis of Composite Blade & Fatigue
        1. Blade Stress Analysis
        2. Material Allowances (Tsai-Wu Criterion)
        3. Final Design - Target Layup
        4. Fatigue and Failure Index
    3. Stress Analysis of Metallic Components
3. **Final Statement**

Stress Analysis of Composite Blade & Fatigue

Tsai-Wu criterion LF into material allowables

Original material data:

Strength parameter	Value /(N/mm²)
R_{11}^{+}	2282
R_{11}^{-}	1067
$\boldsymbol{R_{22}^{+}}$	**30.24**
R_{22}^{-}	200
R_{12}	99
ILS	84.8

For fatigue analysis:
Knockdown factor = 1.3

Strength parameter	Value /(N/mm²)
R_{11}^{+}	1755
R_{11}^{-}	821
$\boldsymbol{R_{22}^{+}}$	**23.26**
R_{22}^{-}	154
R_{12}	76
ILS	65.23

For static analysis:
safety factor = 2.5*knockdown

Strength parameter	Value /(N/mm²)
R_{11}^{+}	702
R_{11}^{-}	328
$\boldsymbol{R_{22}^{+}}$	**9.3**
R_{22}^{-}	62
R_{12}	30.5
ILS	26.1

reduction from 17 to 9.3

Instead of increased load factor a safety factor is applied on the material data and included in the static analysis. This allows a correct calculation of displacements.

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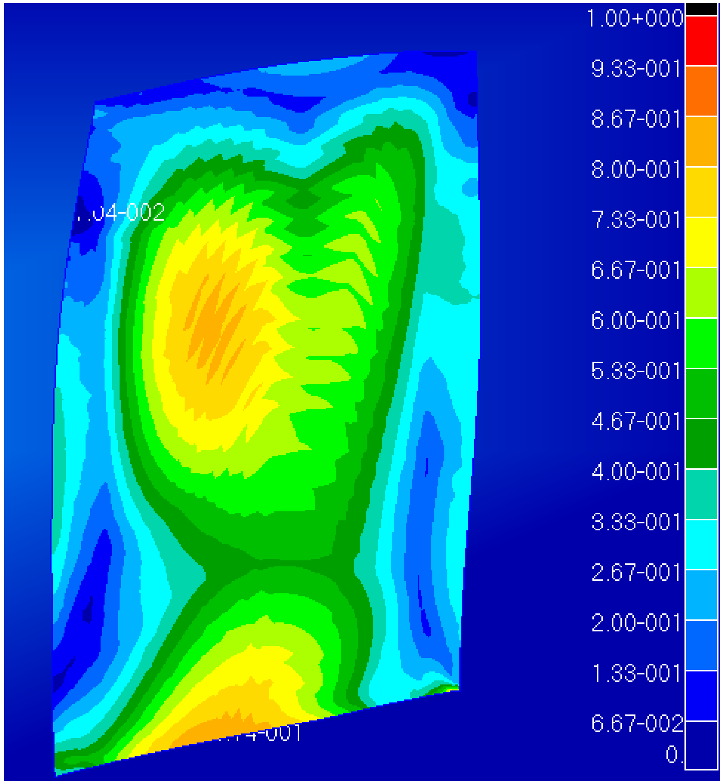
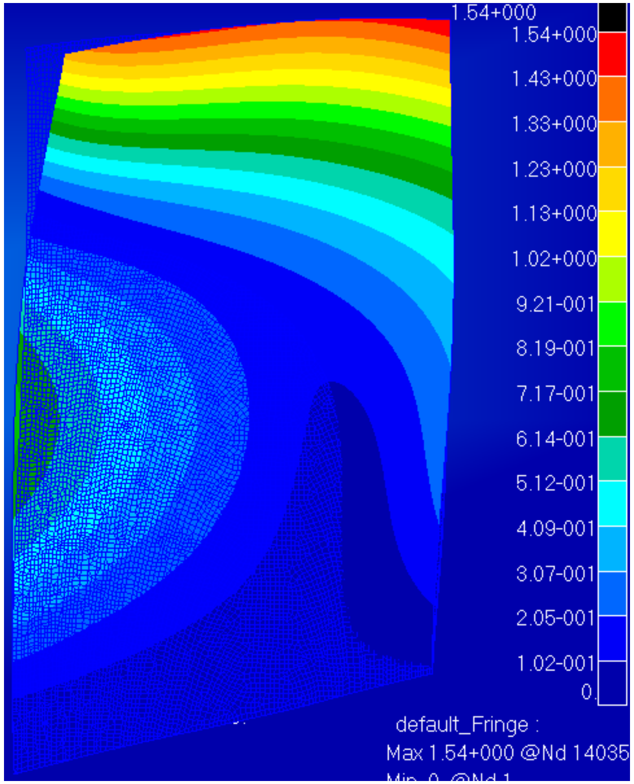
Stress Analysis of Composite Blade & Fatigue

Target Layup - Final Design Condition

Max. failure index = 0.874



Displacements



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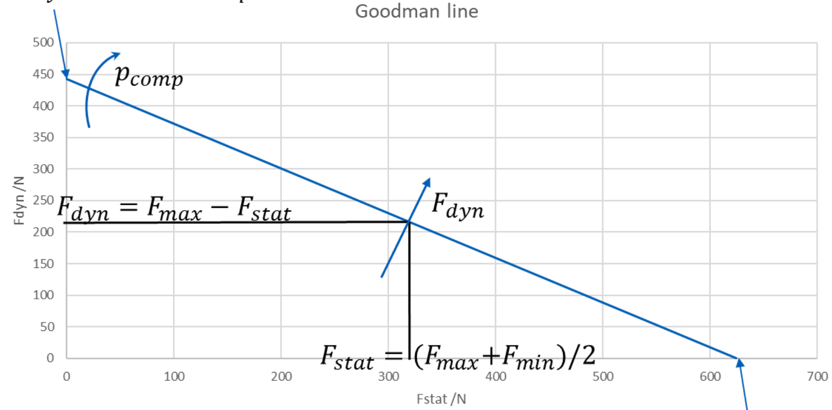
Stress Analysis of Composite Blade & Fatigue

Fatigue

A modified Goodman approach is used to calculate static equivalent loads using the max. and min. forces working on the blade.

$$F_{dyn,eq} = F_{dyn} + F_{stat} \cdot p_{comp}$$



$$F_{stat,eq} = F_{dyn,eq}/p_{comp}$$

Tsai-Wu criterion

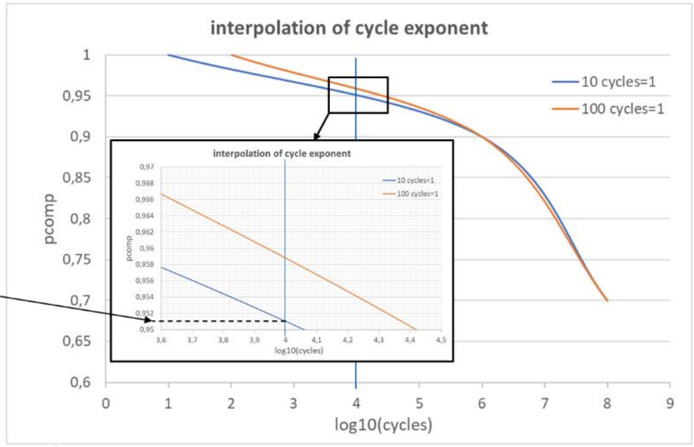
High cycle fatigue (flutter analysis):

p_{comp} for 10^8 cycles = 0.7

Low cycle fatigue (turning on and off):

p_{comp} for 10 cycles = 1

- Zero damage
- Interpolation:
- p_{comp} 10^4 = 0.951



Combined p_{comp} (Accumulated damage) $\quad 1 - \sum_{i=1}^{k} 1 - p_{comp,i} = p_{comp,c} = 1 - 0.049 - 0.3 = \mathbf{0.651}$

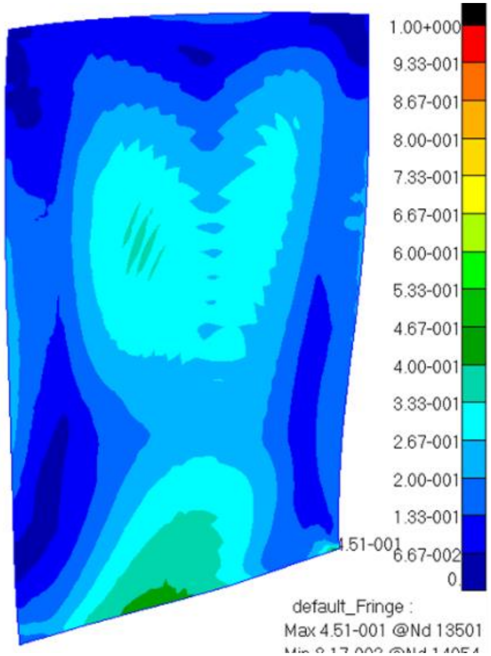
Low cycle reduction high cycle reduction

The performance of the material after the estimated amount of load cycles through the parameter p_comp. This parameter is calculated by following the approach shown in the left picture.

Stress Analysis of Composite Blade & Fatigue

Failure Index

Map of failure index generated by the equivalent static load condition coming from the fatigue analysis, showing structural safety up to 10^4 low-cycles (turning on and off) and 10^8 high-cycles (vibration in forced response or limit-cycle conditions).



Knockdown factor = 1.3

Dyn. Load factor = 1.2

Max. failure index = 0.451

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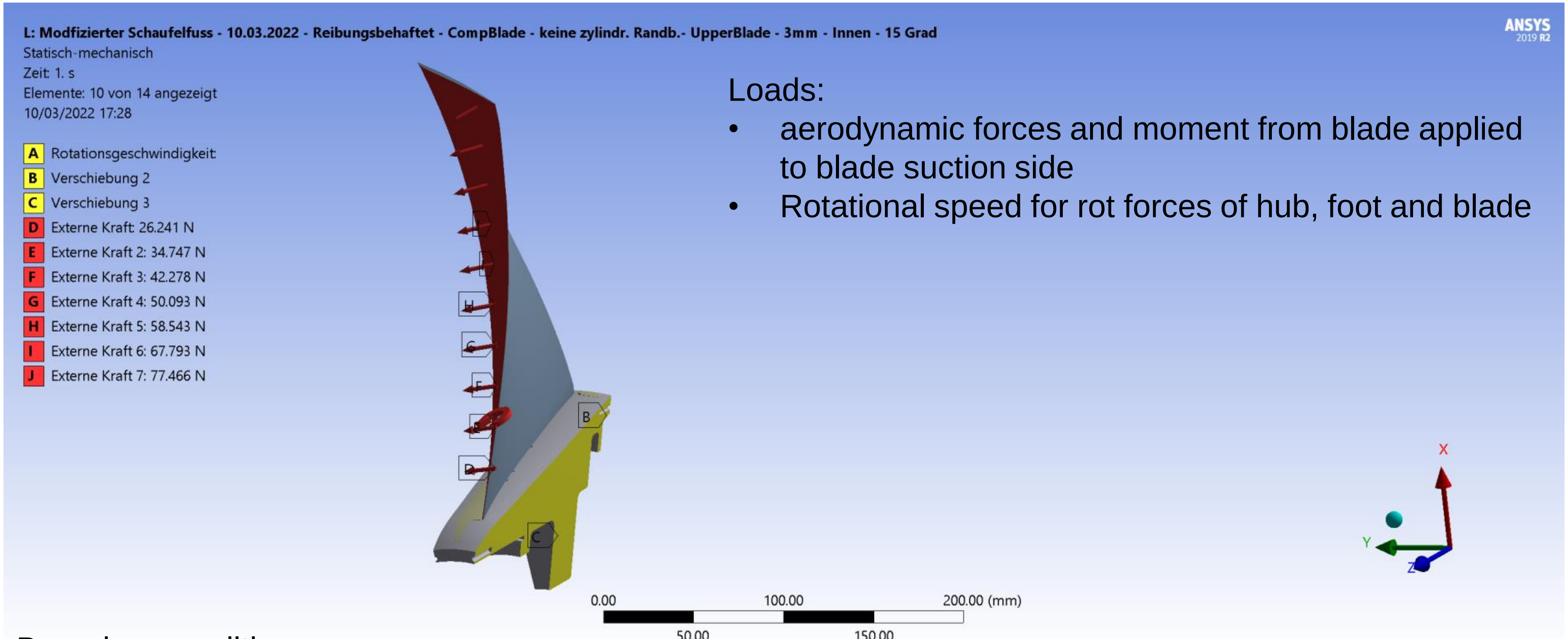
Stress Analysis of Metallic Components

Loads & boundary conditions

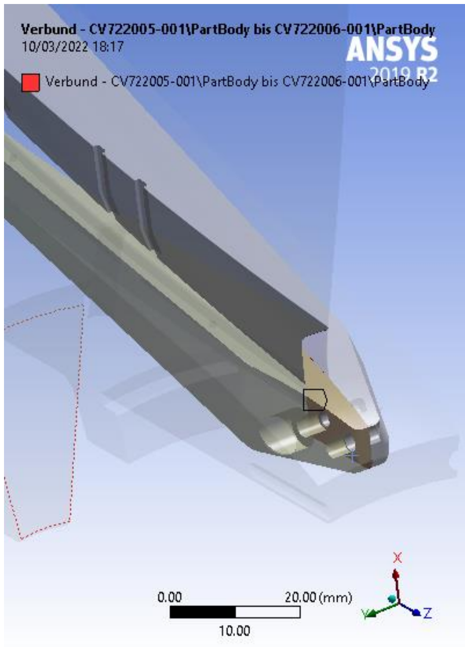


Loads:
- aerodynamic forces and moment from blade applied to blade suction side
- Rotational speed for rot forces of hub, foot and blade

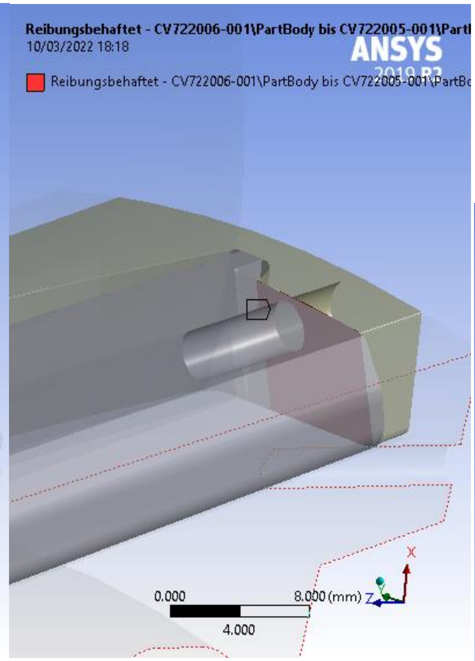
Boundary conditions:
- Circumferential displacements fixed at sides (B)
- Axial displacement fixed at C

Stress Analysis of Metallic Components

Contact Modelling

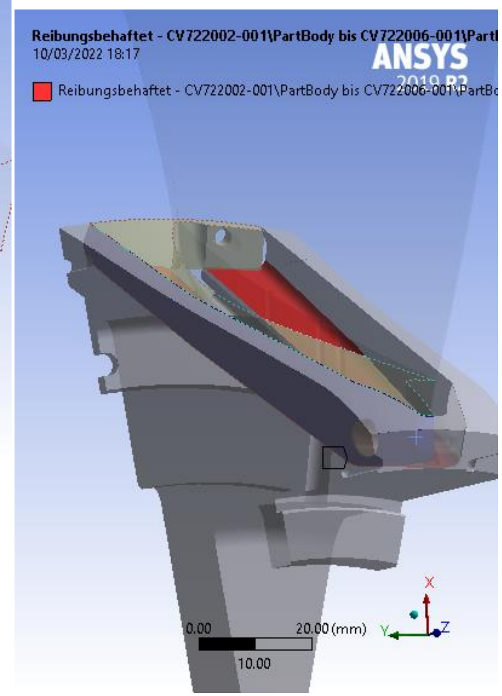


Glued contact at front of foot parts:

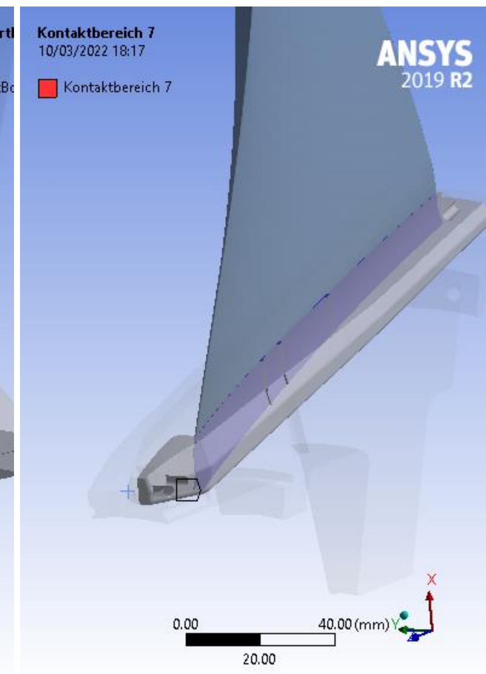


sliding contact and pin at the rear:

Sliding contact between foot parts and hub:



Glued contact between foot parts and blade:



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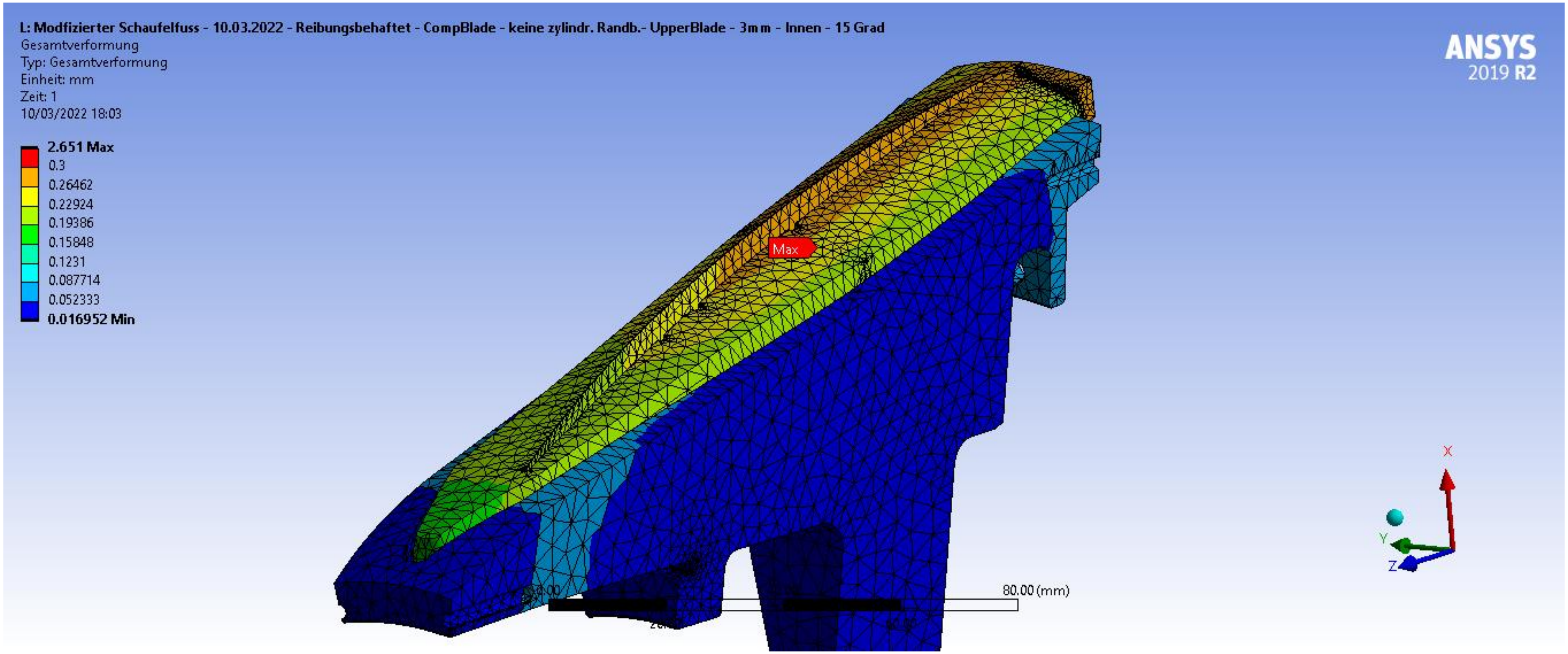
Stress Analysis of Metallic Components

Displacements



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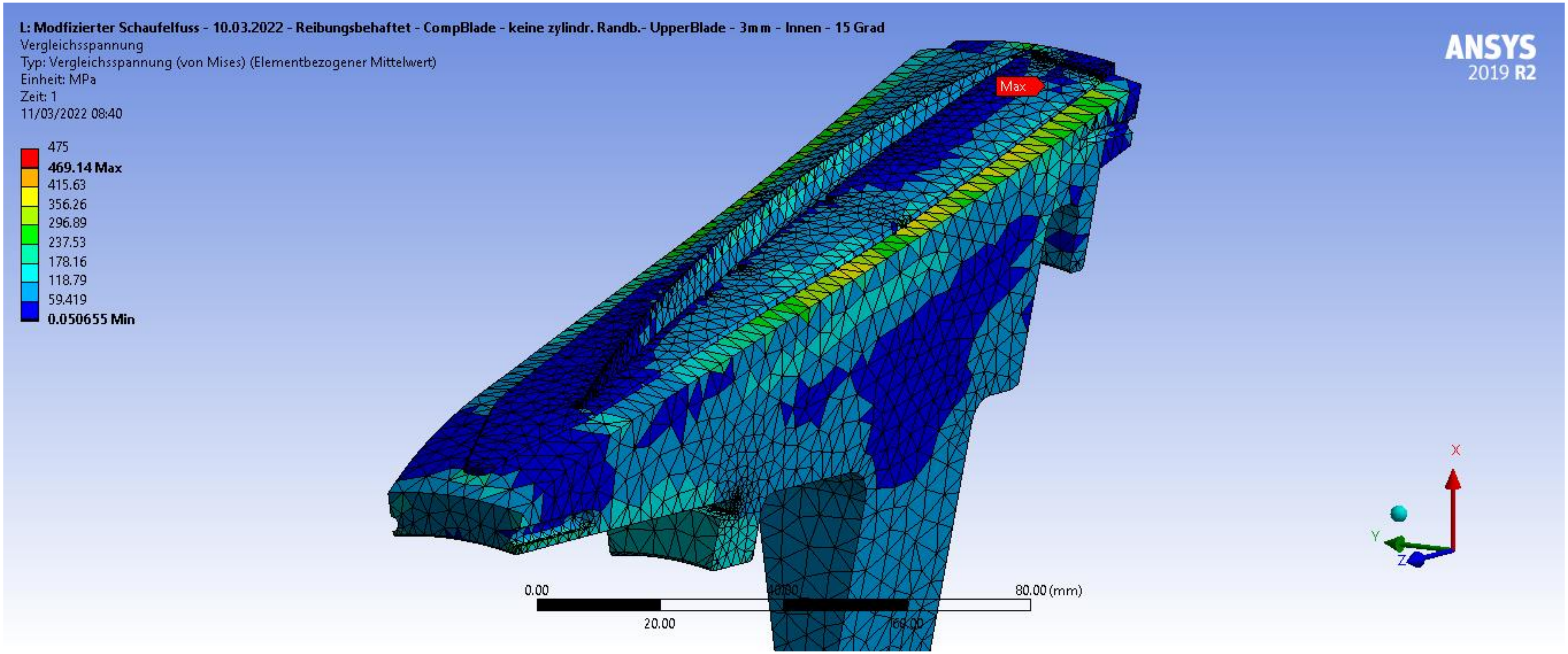
Stress Analysis of Metallic Components

Stress Distribution (v. Mises Stress) – Full Model

Front view:

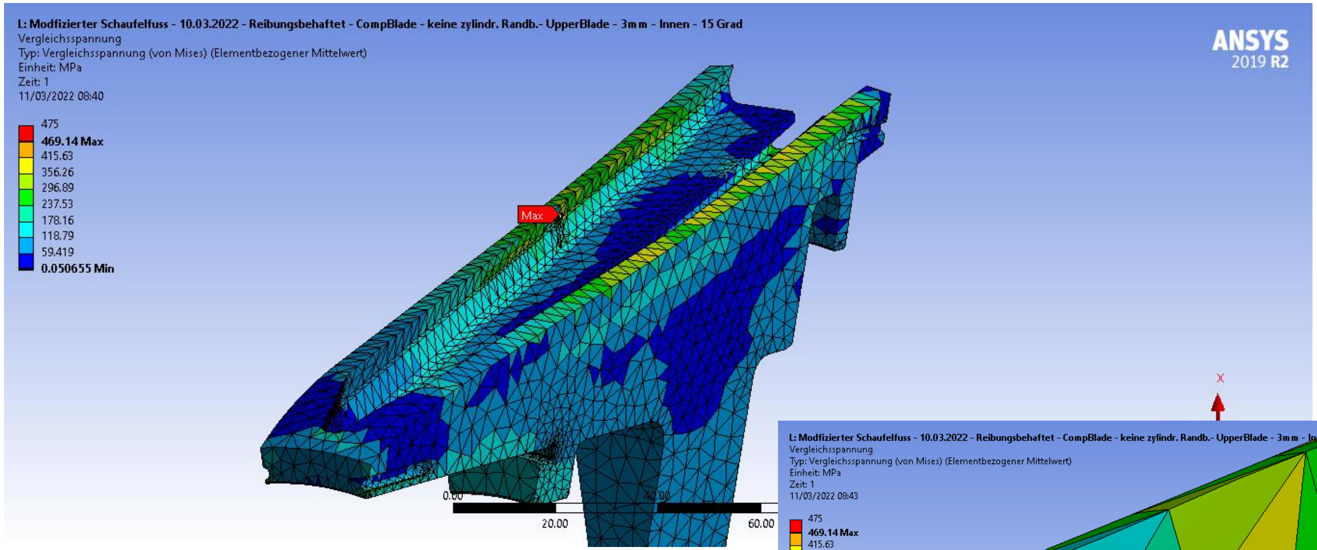


CA3ViAR Dissemination Event #1 - Stress and Fatigue Analysis

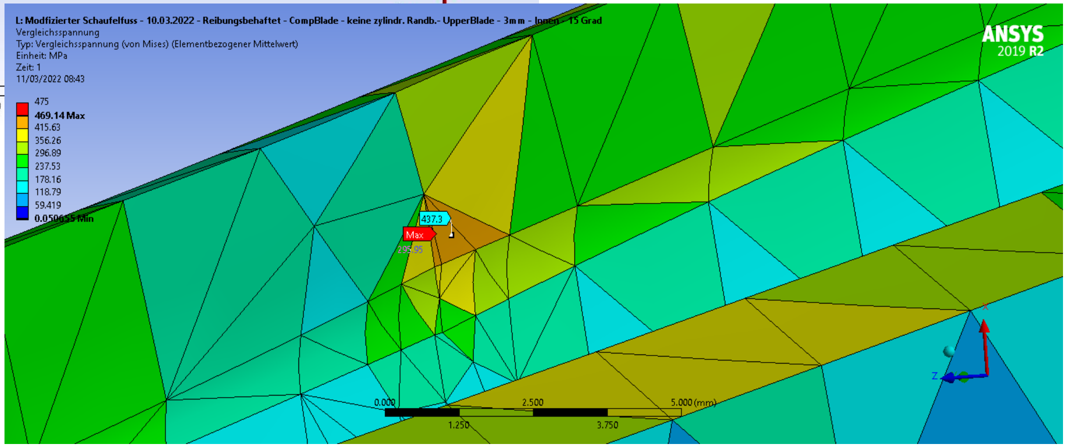
Stress Analysis of Metallic Components

Stress Distribution (v. Mises Stress) – Hub

Front view:



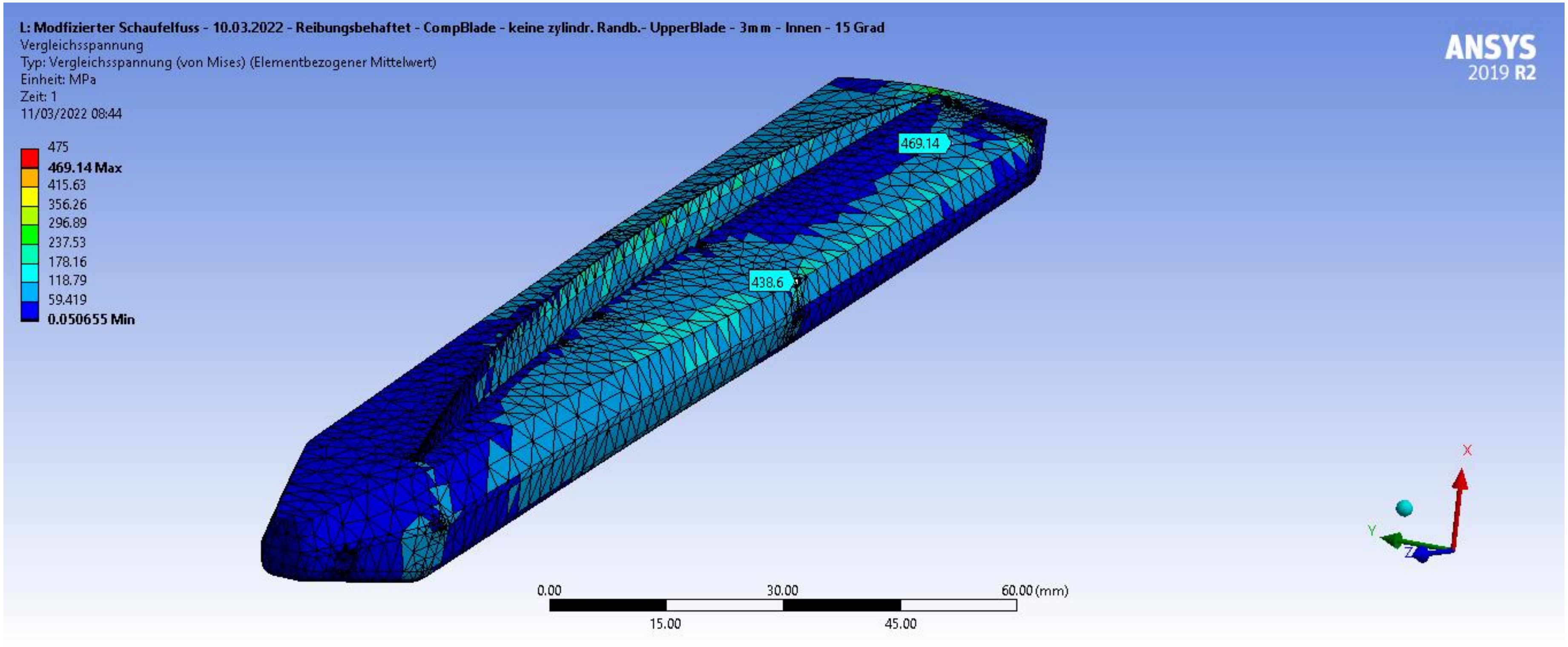
Stress peak 437.3 MPa
RF = 1.09



Stress Analysis of Metallic Components

Stress Distribution (v. Mises Stress) – Foot

Overview and highest stresses:

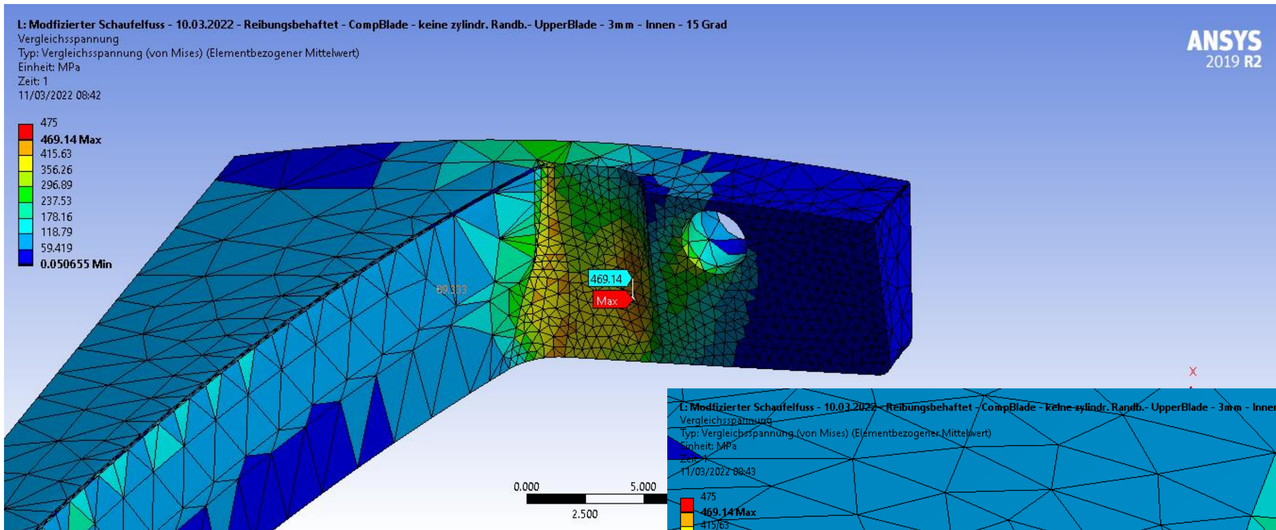


CA3ViAR Dissemination Event #1 - Stress and Fatigue Analysis

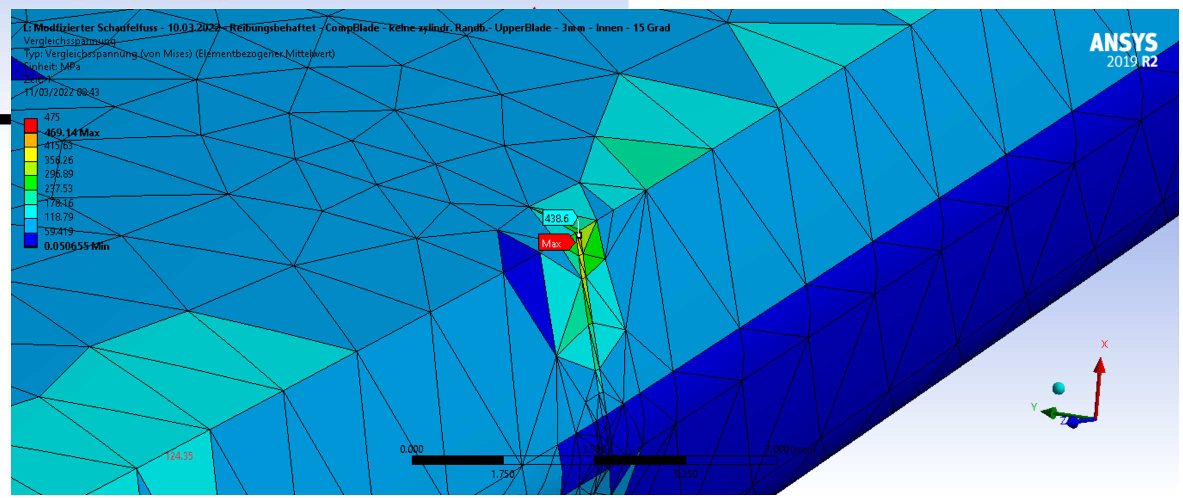
Stress Analysis of Metallic Components

Stress Distribution (v. Mises Stress) – Blade Foot

Highest stressed region is the rear connection of the suction side blade foot



Numerical peak of 469.14MPa
Ramax allowable (incl. SF of 2.4) = 475MPa
-> RF = 1.01



Stress peak of pressure side foot 438.6MPa
-> RF = 1.08

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Final Statement: all the CA3ViAR test article parts are analysed and proved to be safe against static strength and fatigue

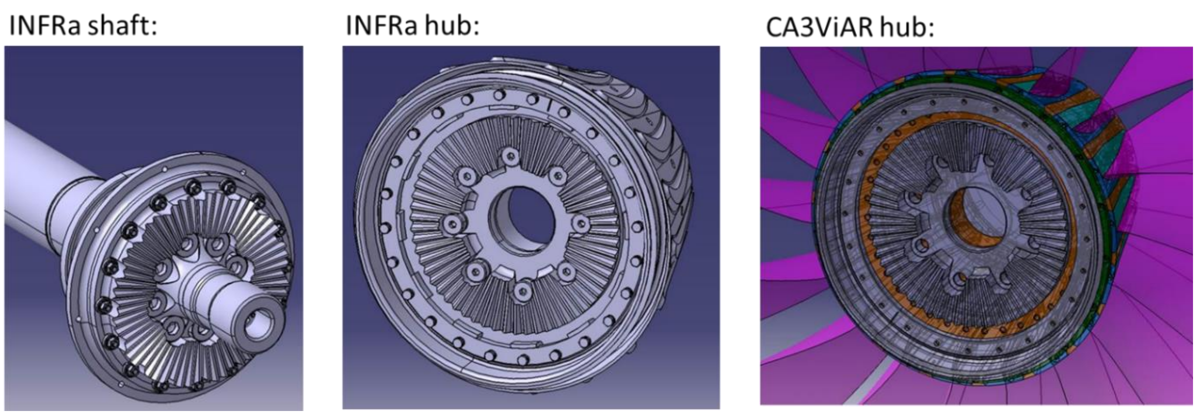
Analysis Shaft to Hub Connection

- Not analysed as part of the CA3ViAR analysis because it is geometrically identical to the INFRa project and has already been analysed and verified by INFRa
- The only difference in CA3ViAR is the hub material, which is stronger. This made the repetition of the analysis not necessary.

Analysis of "1-Blade Loss Condition"

The INFRa shaft will be reused for CA3ViAR. It has already been sized against this condition by using the mass of the INFRa titanium blade, which weight is higher compared to the CA3ViAR CFRP-blade.

- ➢ Therefore, there was no need to perform the 1 blade loss check.



Interfaces of INFRa and CA3ViAR hubs with the rig shaft

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Thank You For Your Attention