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EUROfusion

Structural Integrity Assessment of the Central Outboard Segment of the EU DEMO HCPB Breeding Blanket

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Breeding Blanket Project in EUROfusion

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Outline

1. Introduction to the Design

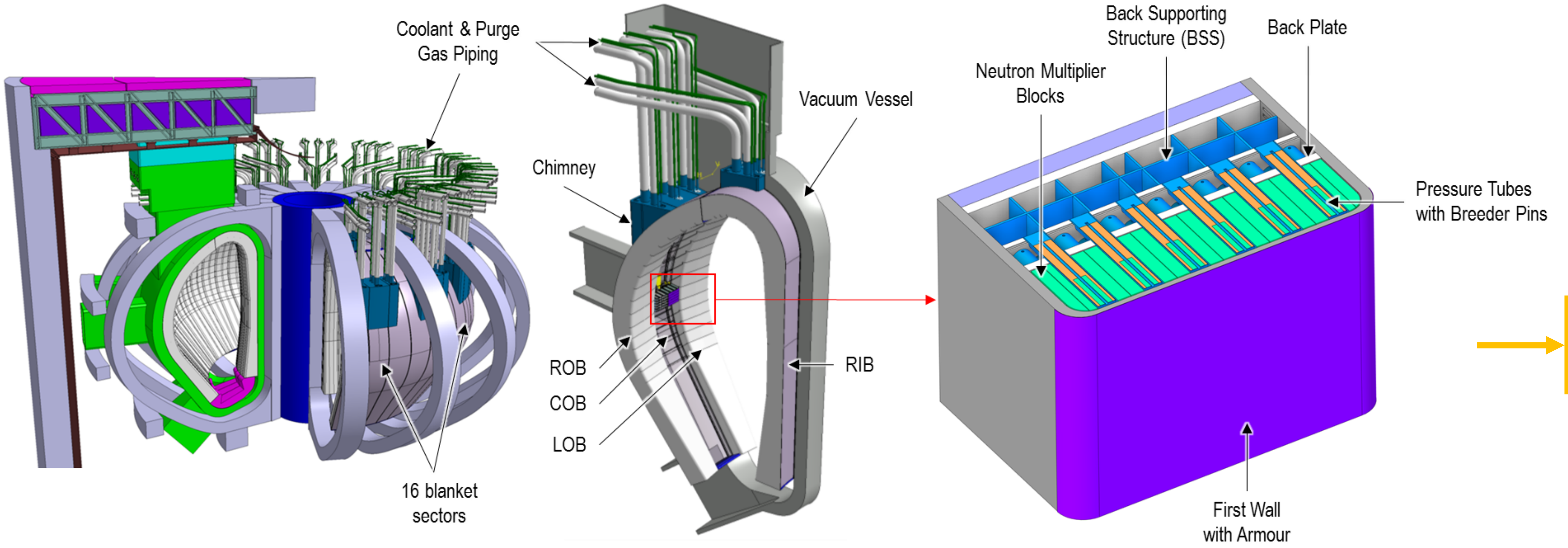
2. Finite Element Modelling

3. Attachment System

4. Results

5. Conclusions

1. Design: Introduction

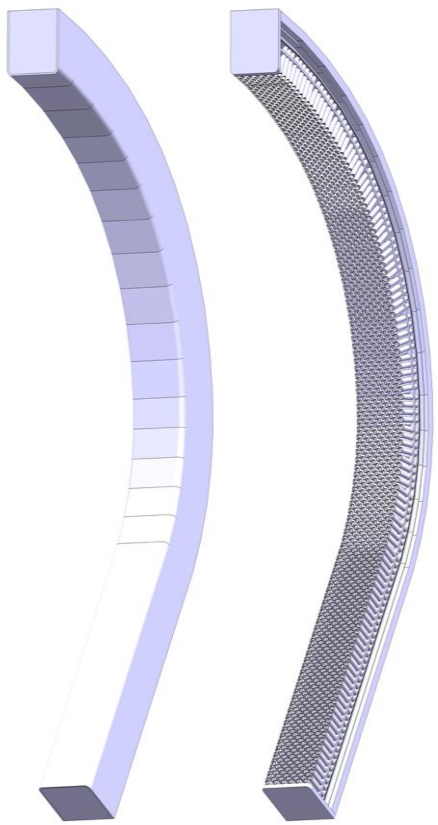


G. Zhou, P1A1
Blanket Technology I

HCPB BB Concept within the DEMO tokamak

- **Coolant**: 80 bar helium gas, T_{in}/T_{out}: 300/520 °C
- **Structural material**: Eurofer97
- **Tritium breeder**: Advanced ceramic breeder (Li4SiO4+35%mol.Li2TiO3)
- **Neutron multiplier**: Be12Ti block
- **Armour**: Tungsten, Functionally Graded Material, 2 mm
- **Tritium extraction**: helium purge gas at 80 bar

1. Design: Central Outboard Segment



Primary Loads:

Gravity

Pressure

Electromagnetic

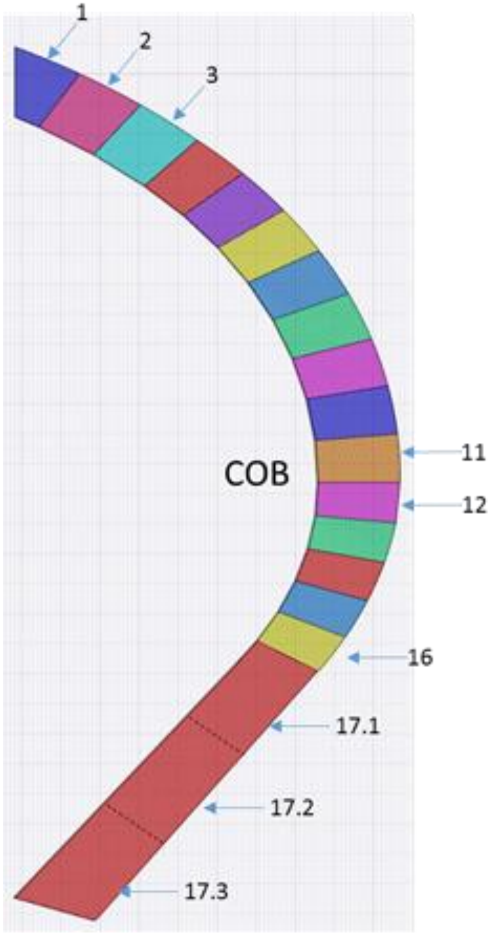
Seismic

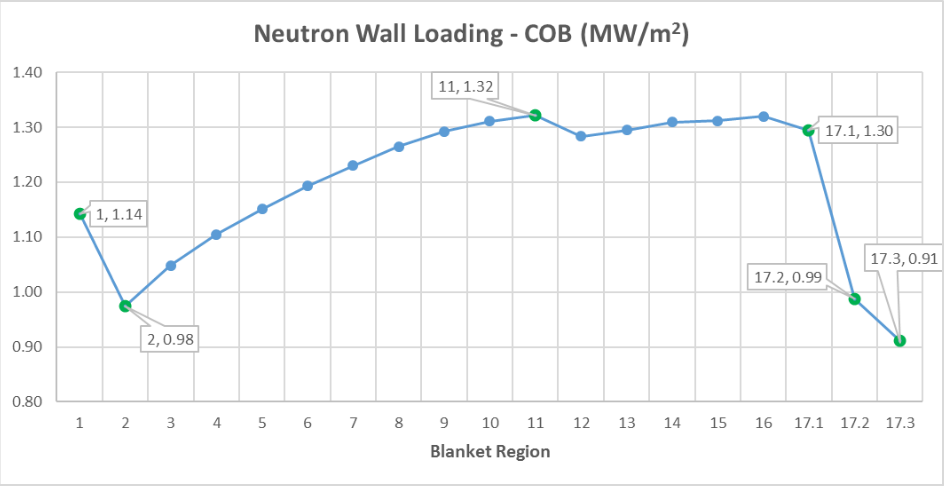
Secondary Loads:

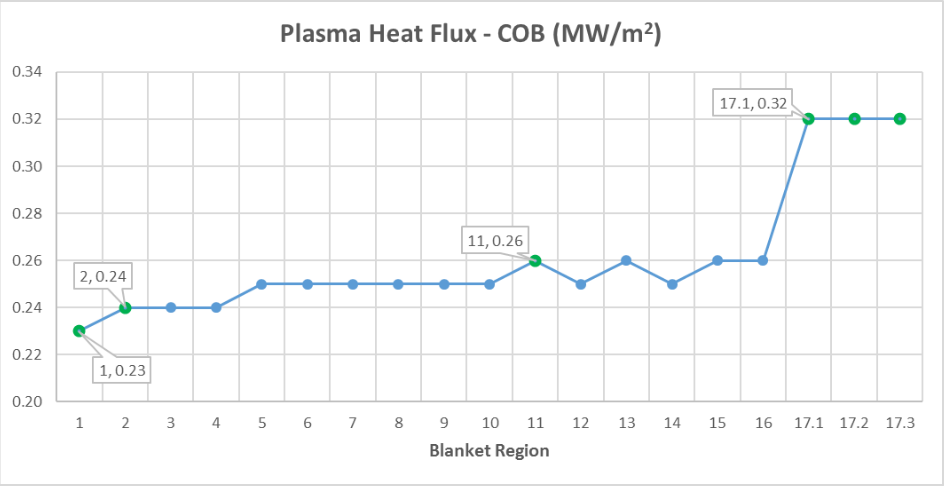
Thermal

Irradiation Swelling

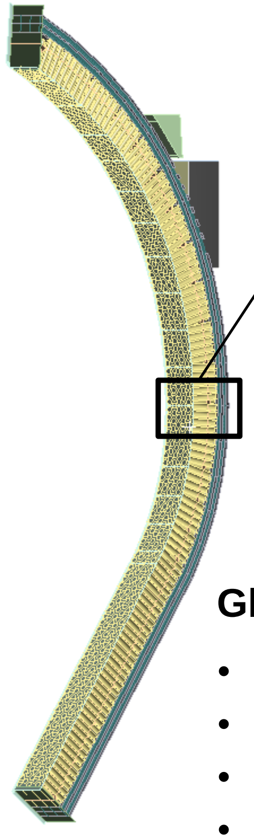
Central Outboard (COB) Segment on Single Module Segment (SMS) Concept

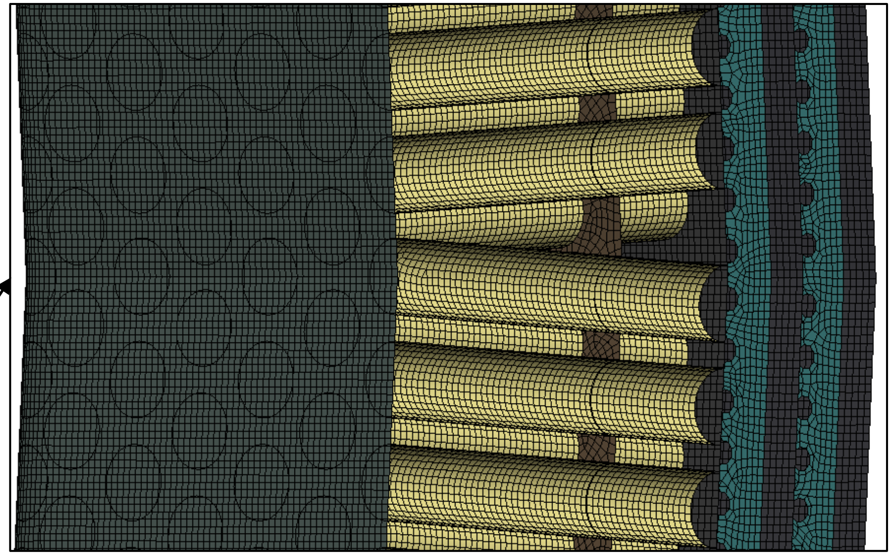






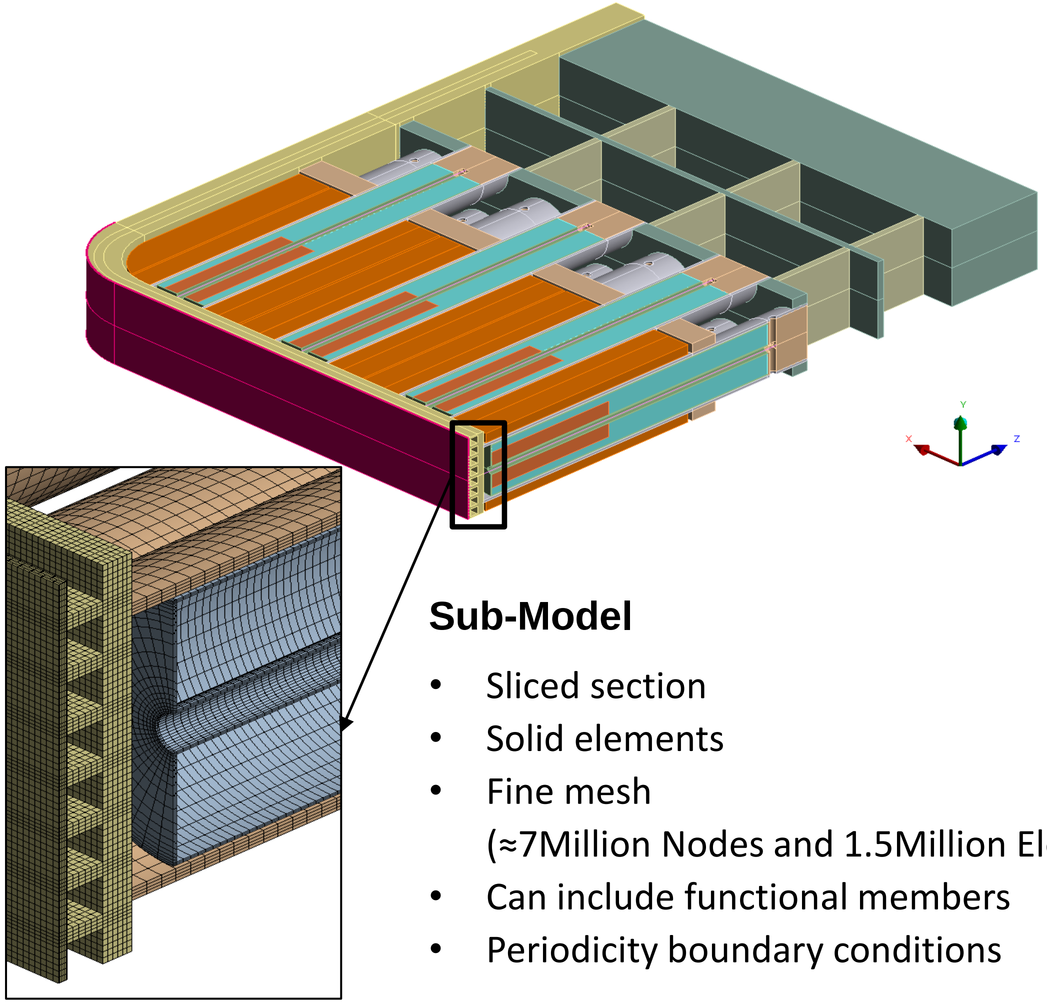
2. Finite Element Modelling: Global and Sub-model





Global Model

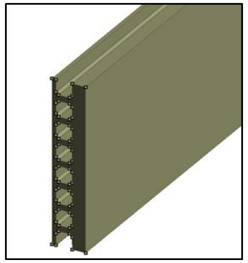
- Reduced DOF model for rapid design exploration
- Shell elements
- Coarse mesh (≈2Million Nodes and Elements)
- Only structural members
- First wall represented by orthotropic layered shell

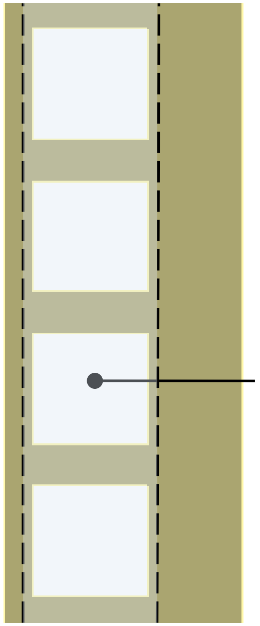


Sub-Model

- Sliced section
- Solid elements
- Fine mesh (≈7Million Nodes and 1.5Million Elements)
- Can include functional members
- Periodicity boundary conditions

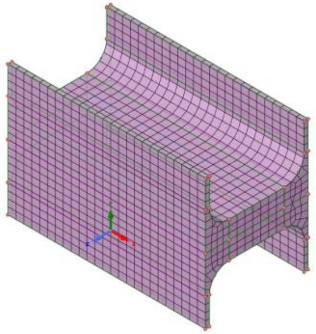
2. Finite Element Modelling: Modelling of first wall





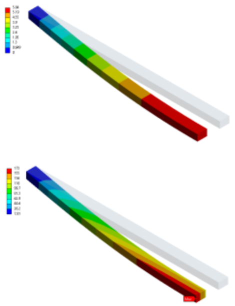
First Wall model

- Trade-off studies between solid, orthotropic shell and layered shell
- Selected 3 layered shell element
- Middle orthotropic layer
- *Ansys Material Designer to* estimate equivalent material properties
- A Representative Volume Element (RVE) is used for the numerical tests

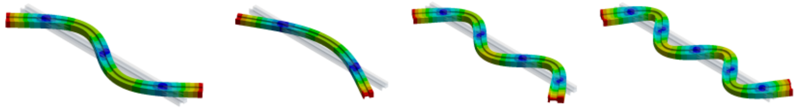


RVE – orthotropic layer

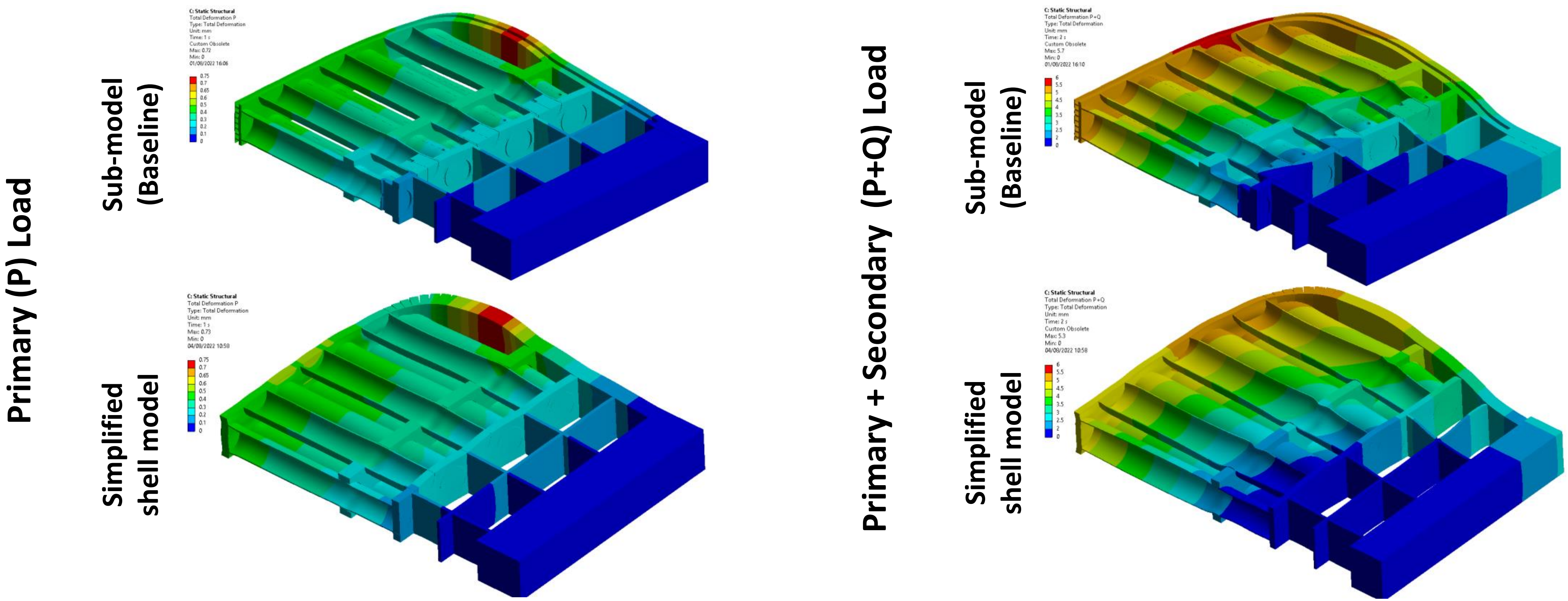
Verification studies: I-beam bending under distributed loading				
	Mesh 1	Mesh 2	Mesh 3	Analytical Solution
Elements	34	200	750	
Nodes	54	255	882	-
Aspect Ratio	3.6	2.4	1.5	
Max. Displacement (mm)	5.84	5.85	5.85	5.69
Error – Displacement	2.6%	2.8%	2.8%	-
Max. Stress (MPa)	173	173	173	169
Error – Stress	2.3%	2.5%	2.5%	-



Verification studies: I-beam natural frequencies			
	Analytical Solution (Hz)	Shell FEM Frequency (Hz)	Error
Mode 1	600	588	2%
Mode 2	1650	1600	3%
Mode 3	3243	3084	5%
Mode 4	5042	4998	1%

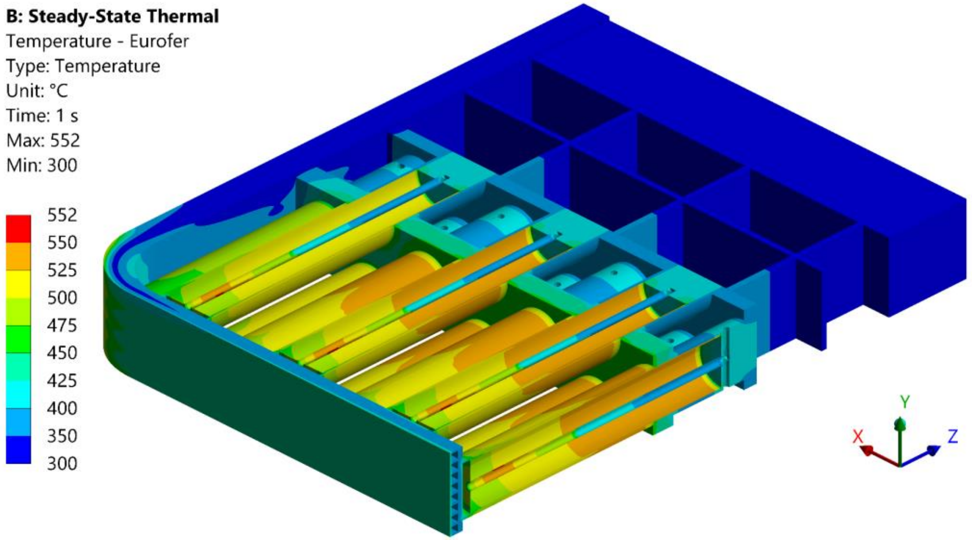


2. Finite Element Modelling: Benchmarking studies



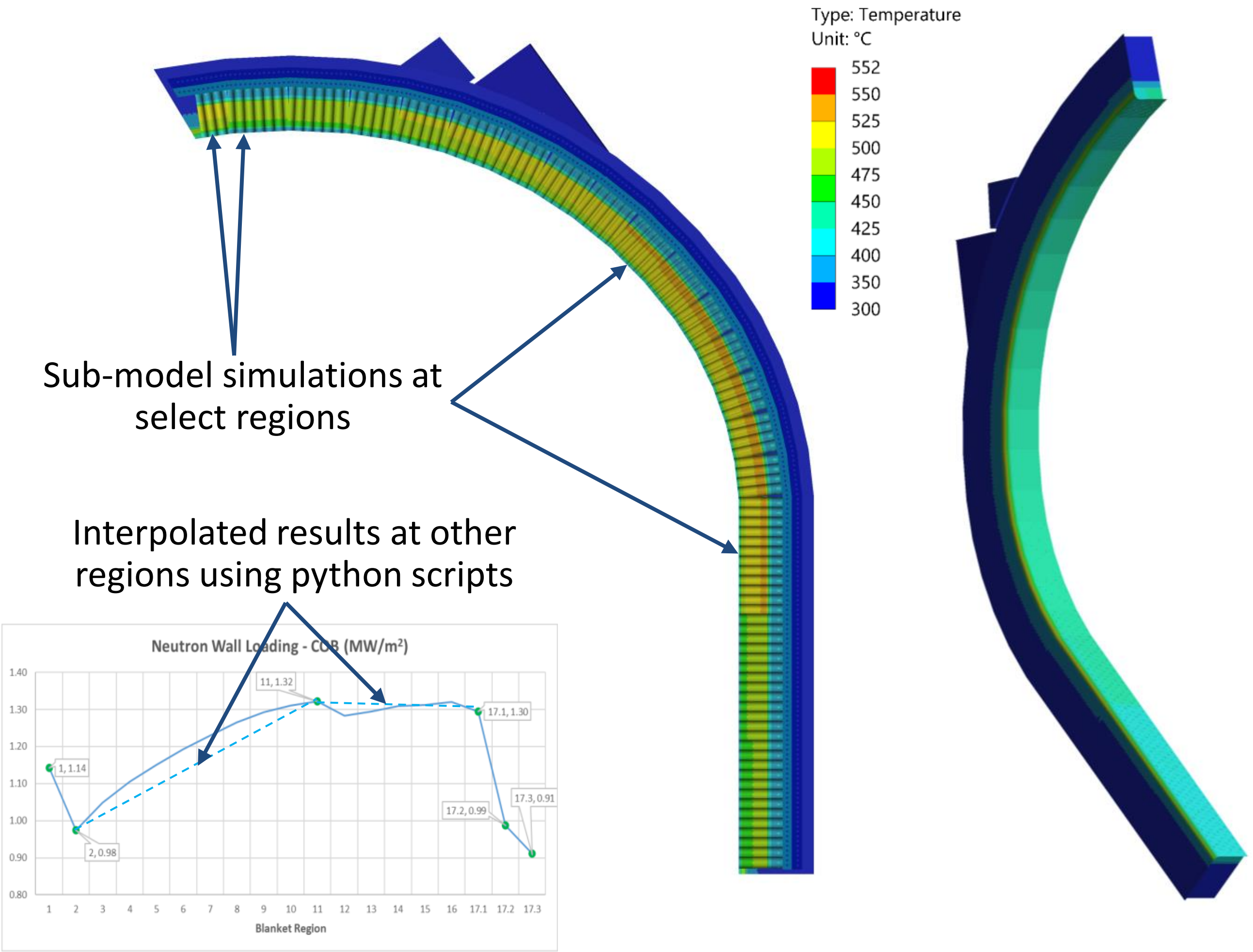
	Elements	Nodes	Avg. Aspect Ratio	Displacement max (mm) P Load	Error Displacement P Load	Displacement max (mm) P+Q Load	Error Displacement P+Q Load
Sub-model (Baseline)	1.5Million	7.1Million	3.8	0.72	NA	5.68	NA
Simplified shell model	16328	17513	1.2	0.73	2.5%	5.30	6.7%

2. Finite Element Modelling: Thermal loads mapping



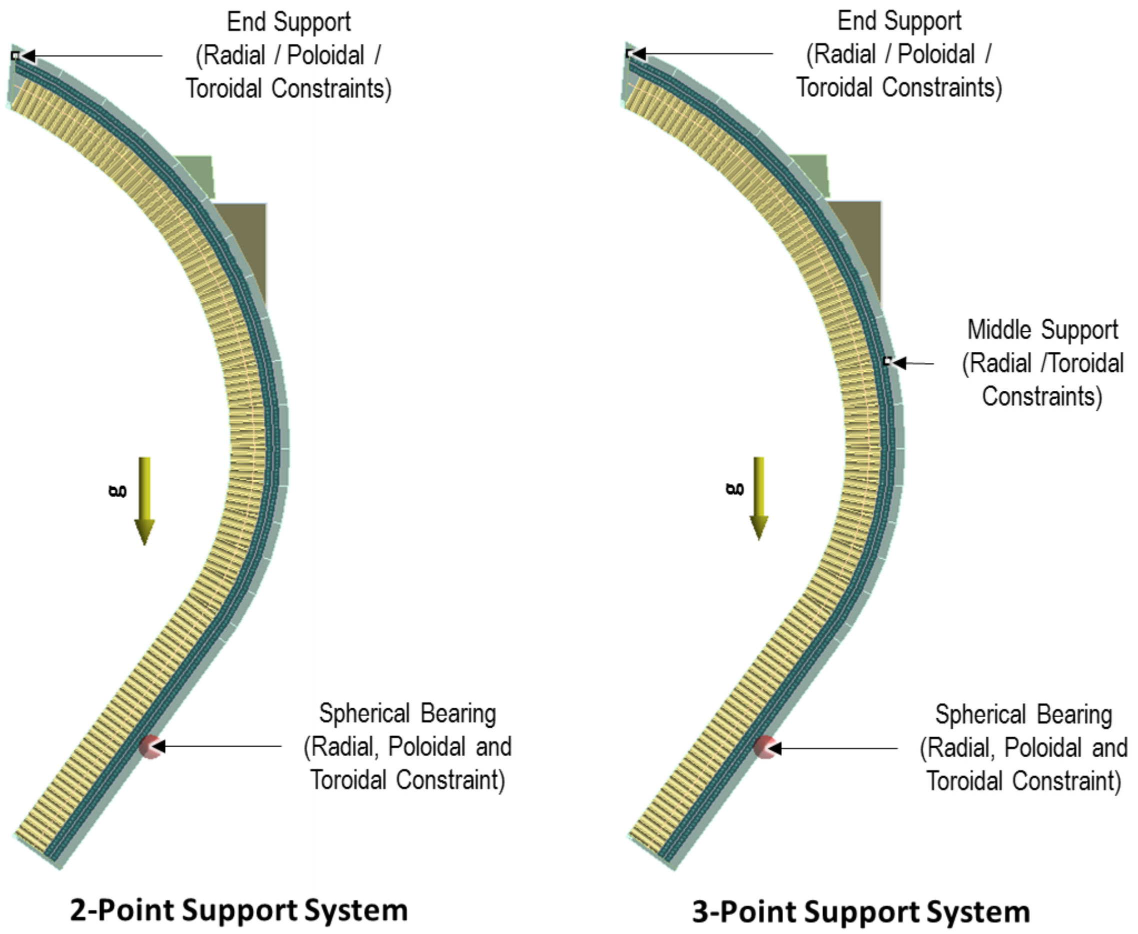
Sub-model Thermo-hydraulics analysis

- Steady state corresponding to normal operation
- Assumed poloidal symmetry
- 1D fluid lines for modelling Helium coolant
- 35g/s at first wall and 21.7g/s at breeder zone
- HTC approximated using *Gnielinski* correlation
- Fusion flux as surface heat flux
- Neutron wall loads as volumetric heat generation



Temperature Distribution on the Global Model

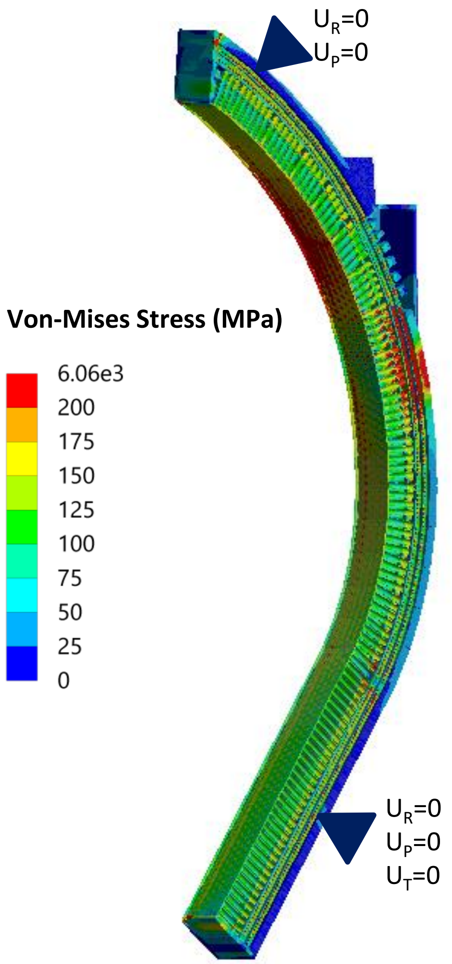
3. Attachment System



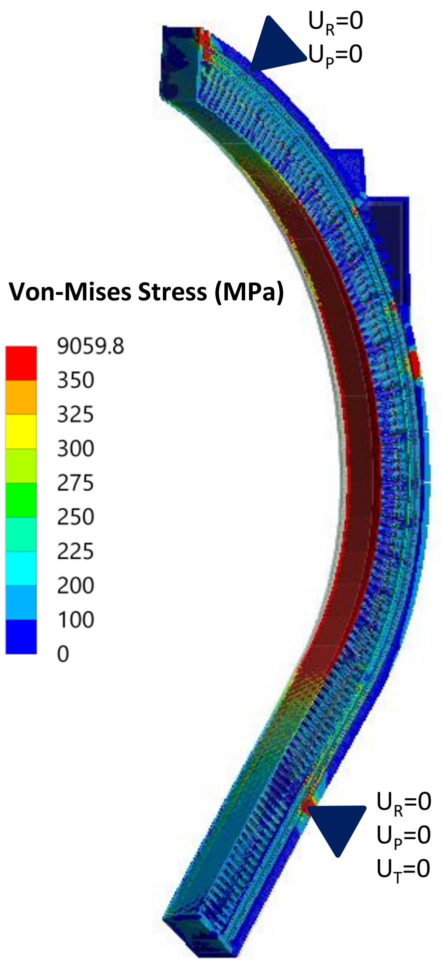
Design Requirements

- Support the segments under gravity & seismic loads
- Minimize thermal stresses
- Support EM Loads during operation
- Avoid contact to vacuum vessel
- Remote handling friendly

Refer: ESTEYCO, HCPB and Blanket Attachment System Global Structural Analyses, 2022, EFDA_D_2QQNVG



Primary (P) Loading

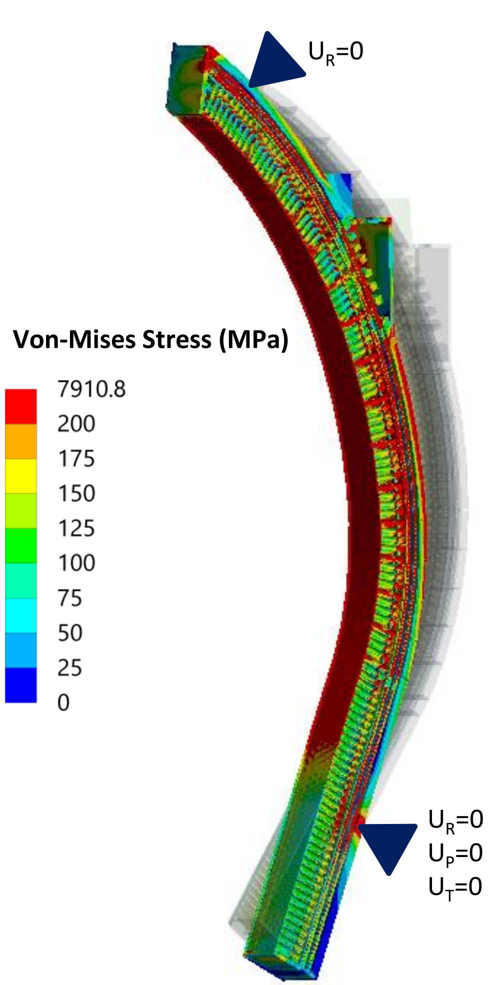


Primary + Secondary (P+Q) Loading

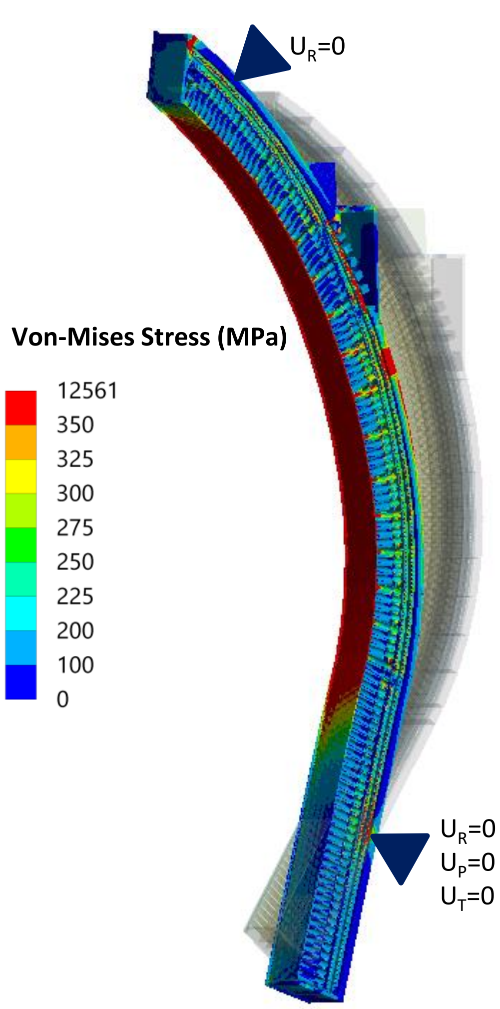
Design Option 1

- Supports the assembly well against primary loading
- High thermal stresses due to constrained poloidal expansion

4. Results



Primary (P) Loading

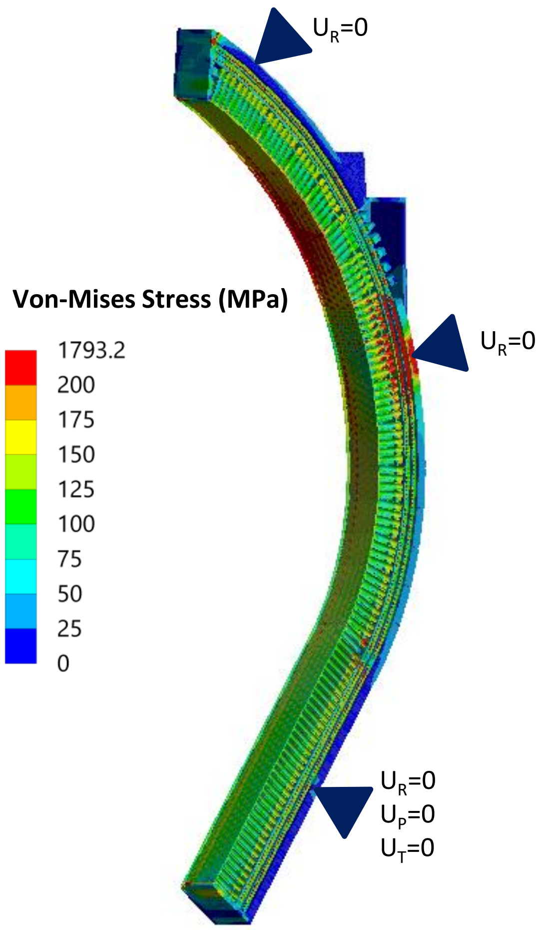


Primary + Secondary (P+Q) Loading

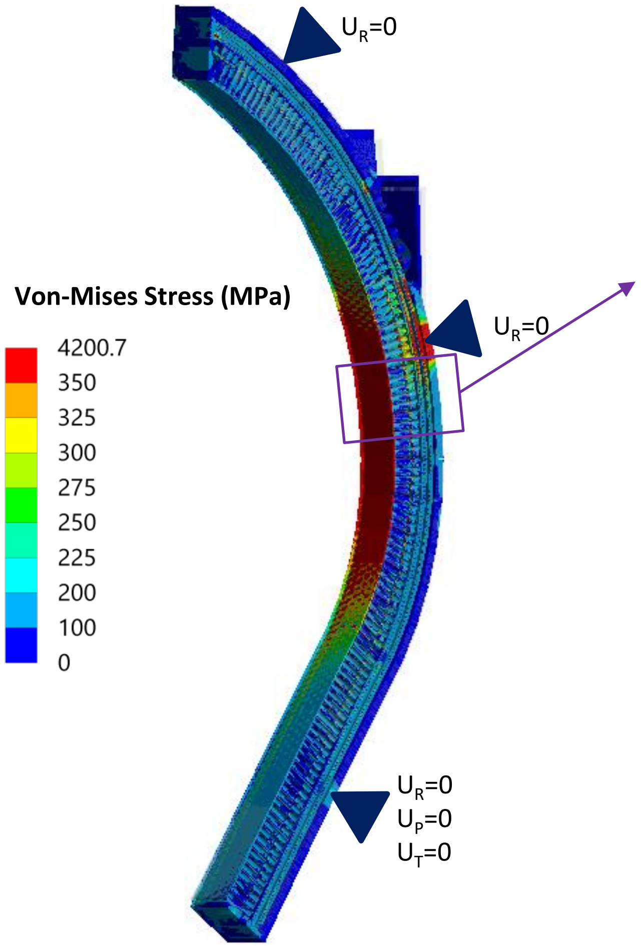
Design Option 2

- Free poloidal expansion resulting in unbending of the structure causing high stresses

4. Results



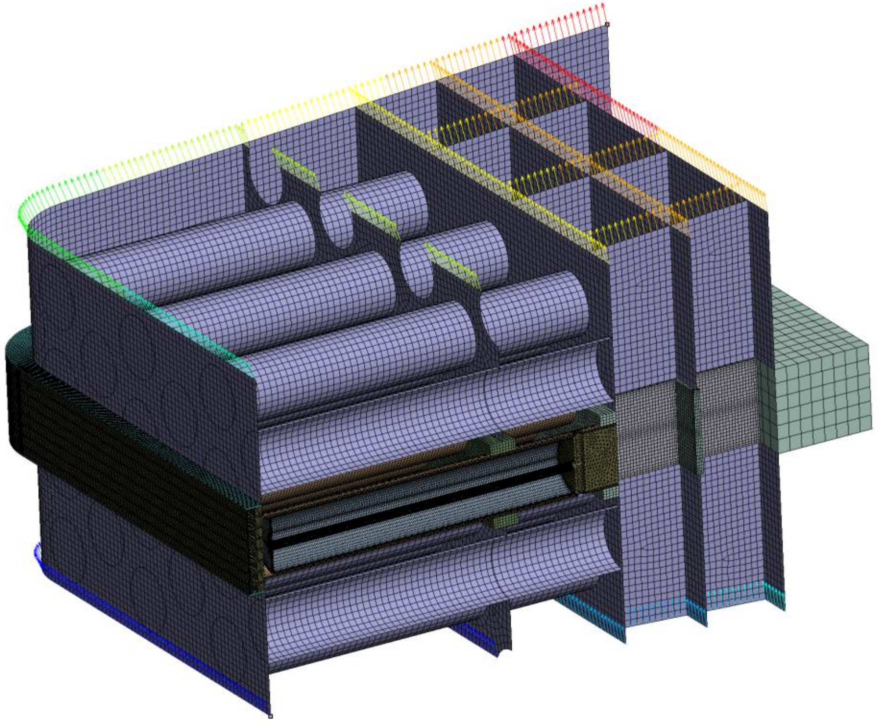
Primary (P) Loading



Primary + Secondary (P+Q) Loading

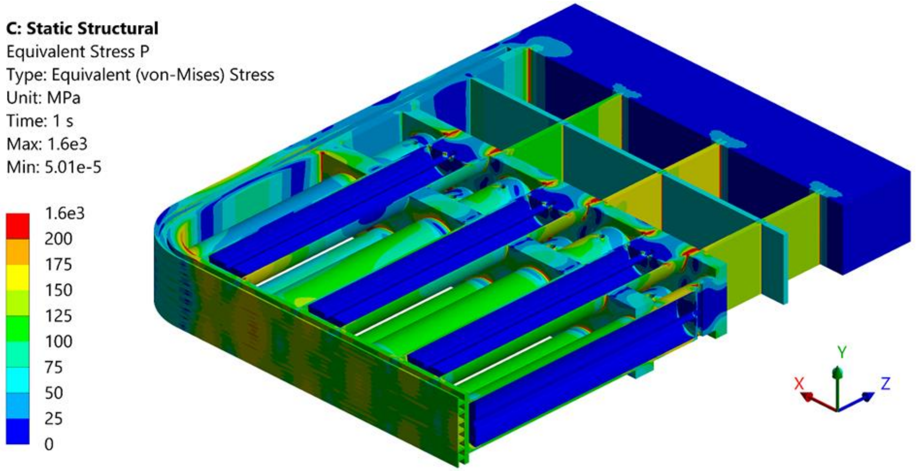
Design Option 3

- Supports the assembly well against primary loading
- Secondary thermal stresses are still high – but less than option 1
- Sub-model simulation driven using global displacements at this location

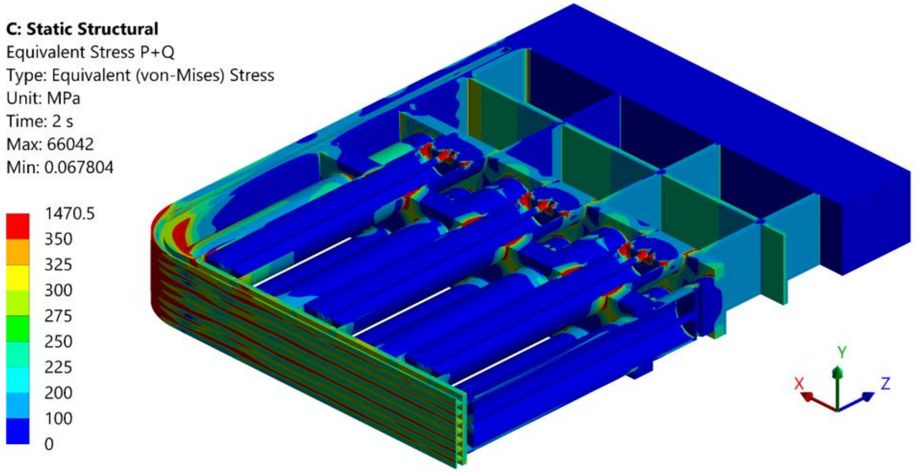


Sub-model results under plane strain conditions

Primary (P) Load

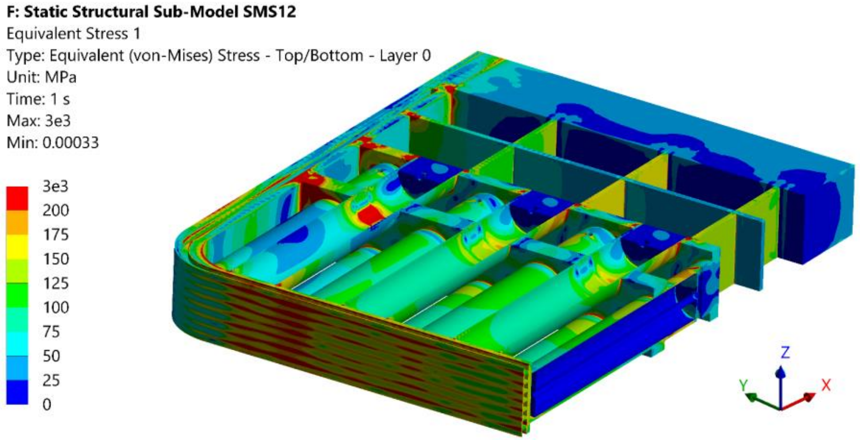


Primary + Secondary (P+Q) Load

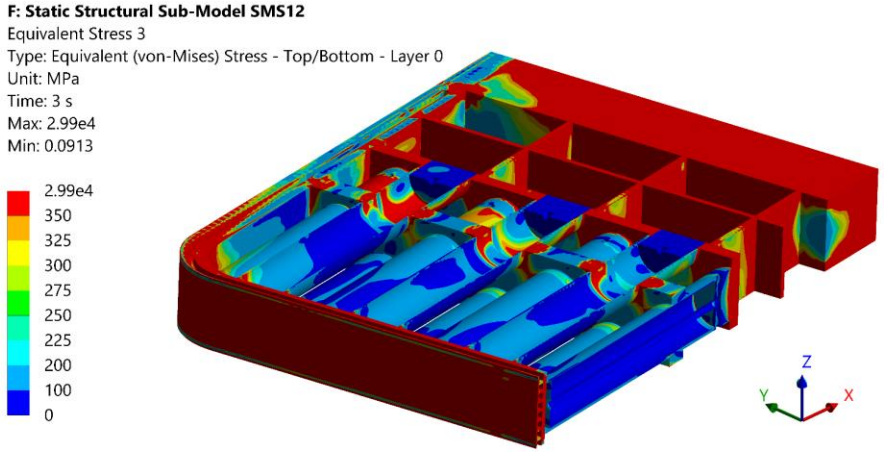


Sub-model results using global model displacements

Primary (P) Load



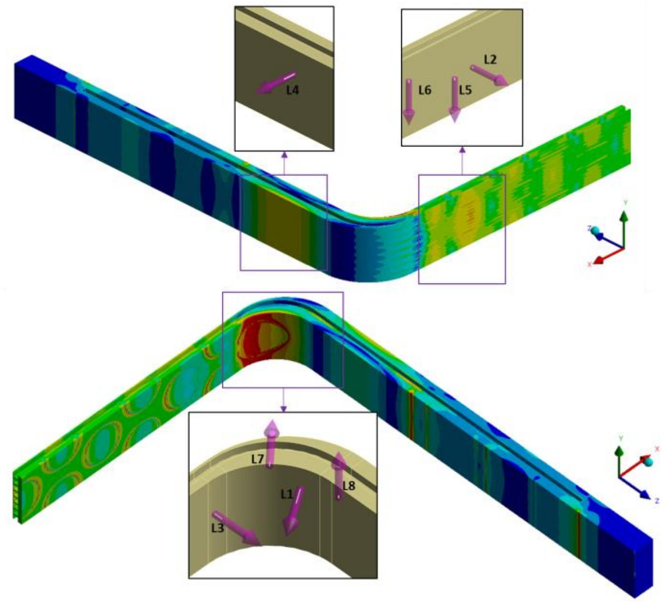
Primary + Secondary (P+Q) Load



4. Results

Stress assessment results for first wall slice under plane strain conditions

Immediate Plastic Collapse (IPC), Instability (IPI) and Plastic Flow Localization (IPFL) & Progressive Deformation (PD)													
Path	T_{avg} (°C)	$\overline{P_m}$ Value (MPa)	S_m^A Limit (MPa)	IPC Margin	$\overline{P_l + P_b}$ Value (MPa)	$1.5 \times S_m^A$ Limit (MPa)	IPI Margin	$\overline{P_m + Q_m}$ Value (MPa)	S_{em}^A Limit (MPa)	IPFL Margin	$\overline{P_l + P_b + \Delta Q}$ Value (MPa)	$3 \times S_m^A$ Limit (MPa)	PD Margin
L1	411	81	169	✓ 52%	157	253	✓ 38%	265	310	✓ 15%	465	507	! 8%
L2	419	167	167	! 0%	178	250	✓ 29%	285	313	! 9%	319	500	✓ 36%
L3	385	134	175	✓ 23%	210	263	✓ 20%	256	301	✓ 15%	314	525	✓ 40%
L4	366	114	179	✓ 37%	169	269	✓ 37%	119	295	✓ 60%	180	538	✓ 67%
L5	353	133	182	✓ 27%	135	273	✓ 51%	359	290	✗ -24%	363	546	✓ 34%
L6	349	152	183	✓ 17%	153	274	✓ 44%	395	287	✗ -37%	399	548	✓ 27%
L7	443	30	160	✓ 81%	44	240	✓ 82%	299	321	! 7%	424	480	✓ 12%
L8	332	165	186	✓ 11%	165	279	✓ 41%	389	288	✗ -35%	393	557	✓ 30%



Initial stress assessment for first wall using Sub-model results

Immediate Plastic Collapse (IPC), Instability (IPI) and Plastic Flow Localization (IPFL) & Progressive Deformation (PD)													
Path	T_{avg} (°C)	$\overline{P_m}$ Value (MPa)	S_m^A Limit (MPa)	IPC Margin	$\overline{P_l + P_b}$ Value (MPa)	$1.5 \times S_m^A$ Limit (MPa)	IPI Margin	$\overline{P_m + Q_m}$ Value (MPa)	S_{em}^A Limit (MPa)	IPFL Margin	$\overline{P_l + P_b + \Delta Q}$ Value (MPa)	$3 \times S_m^A$ Limit (MPa)	PD Margin
L1	411	113	169	✓ 33%	189	253	✓ 25%	432	310	✗ -39%	576	507	✗ -14%
L2	419	199	167	✗ -19%	214	250	✓ 14%	550	313	✗ -76%	593	500	✗ -18%
L3	385	172	175	! 2%	235	263	✓ 11%	472	301	✗ -57%	491	525	! 6%
L4	366	150	179	✓ 16%	216	269	✓ 20%	281	295	! 5%	362	538	✓ 33%
L5	353	146	182	✓ 20%	146	273	✓ 46%	442	290	✗ -52%	447	546	✓ 18%
L6	349	146	183	✓ 20%	148	274	✓ 46%	442	287	✗ -54%	446	548	✓ 19%
L7	443	49	160	✓ 69%	54	240	✓ 77%	514	321	✗ -60%	621	480	✗ -29%
L8	332	173	186	! 7%	173	279	✓ 38%	469	288	✗ -63%	474	557	✓ 15%

5. Conclusions

Summary:

- Method for reduced FE representation of the whole HCPB BB segment
- Explored different attachment systems and its effects on blanket design
- High secondary thermal stress could be a challenge for SMS concepts

Further work plans:

- Improve the global model – remove toroidal symmetry, better thermal loads mapping
- Extend studies to include electromagnetic and seismic loads - normal and off-normal operations
- Explore design options to relief thermal stresses
- Inelastic analysis for assessment of plastic strain limits under secondary thermal load*

Refer: Retheesh, A., Hernández, F. A. & Zhou, G. Application of Inelastic Method and Its Comparison with Elastic Method for the Assessment of In-Box LOCA Event on EU DEMO HCPB Breeding Blanket Cap Region. Applied Sciences 11, 9104 (2021)