ISFNT15
INTERNATIONAL SYMPOSIUM ON FUSION NUCLEAR TECHNOLOGY

10-15
SEPT 2023
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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

IPP CR cea KIT ENEA INSTITUTE OF SOLID STATE PHYSICS UNIVERSITY OF LATVIA ifa Laboratorio Nacional de Fusión Ciemat CCFE

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Outline

1. **Introduction to the Design**

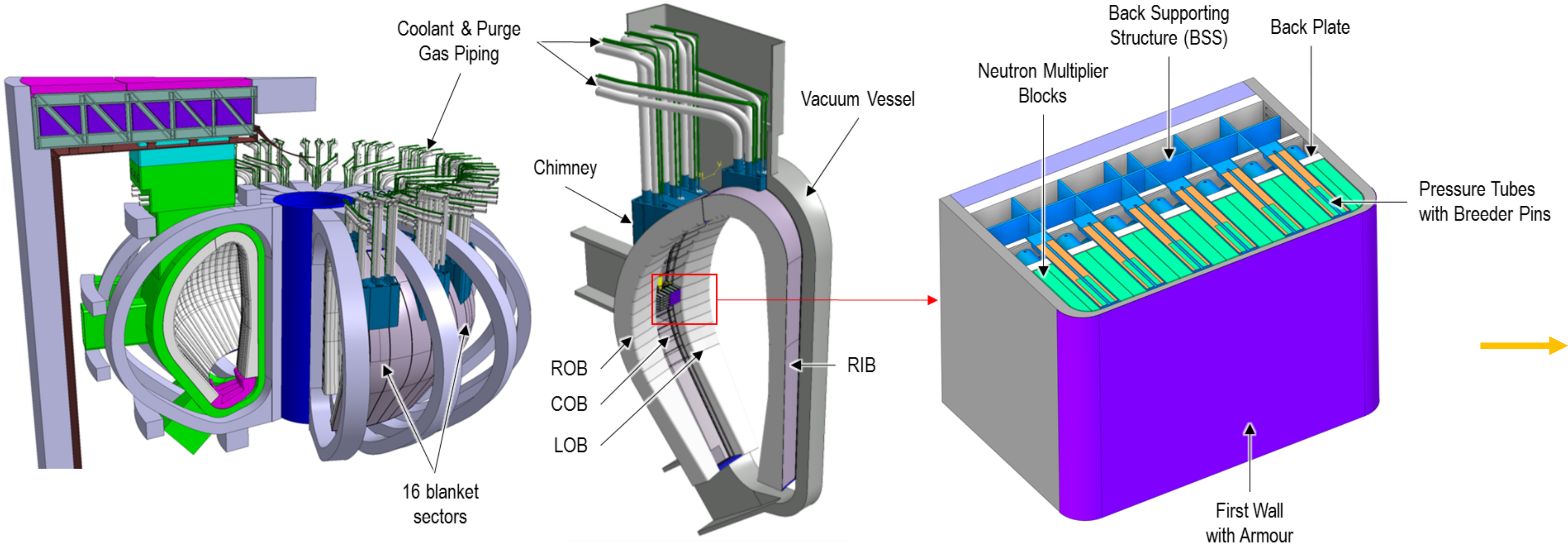
2. **Finite Element Modelling**

3. **Attachment System**

4. **Results**

5. **Conclusions**

1. Design: Introduction

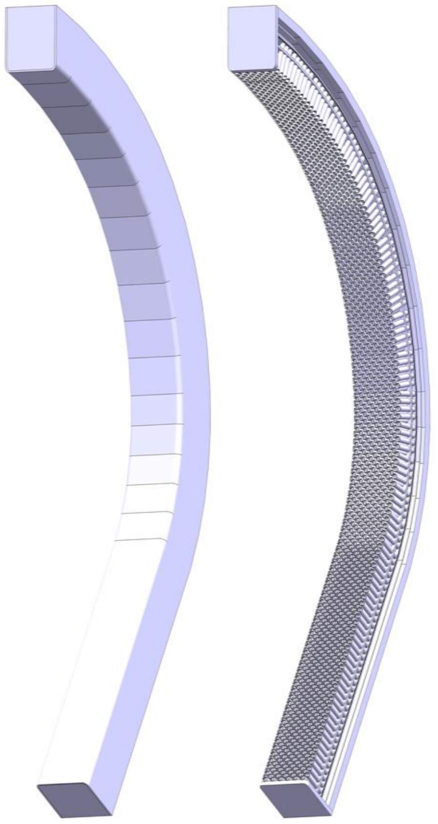


G. Zhou, P1A1
Blanket Technology I

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

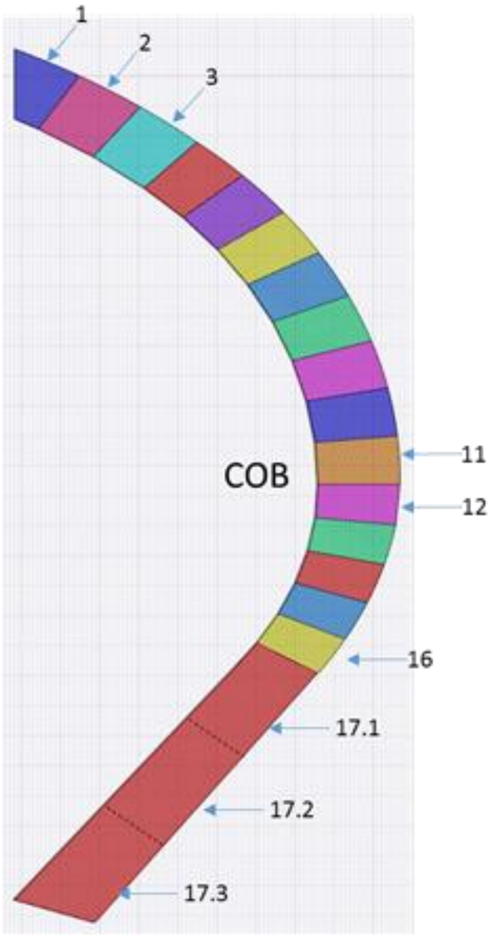
Seismic

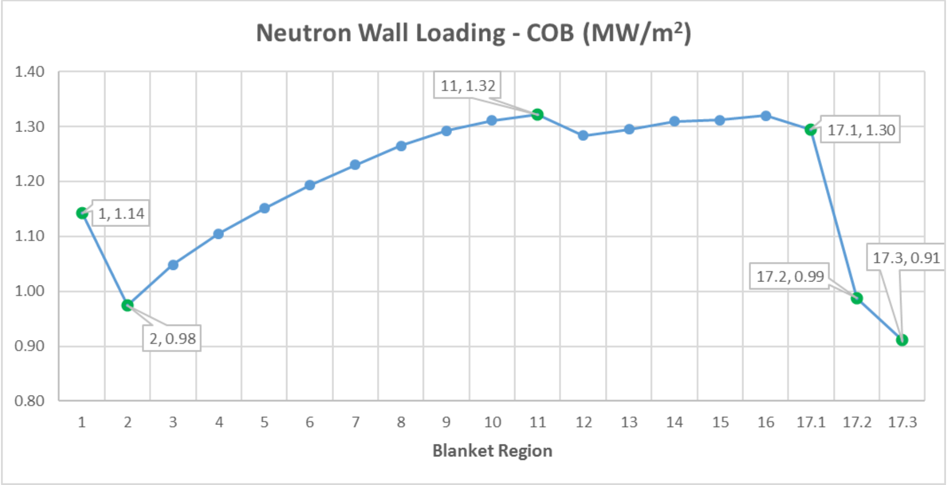
Secondary Loads:

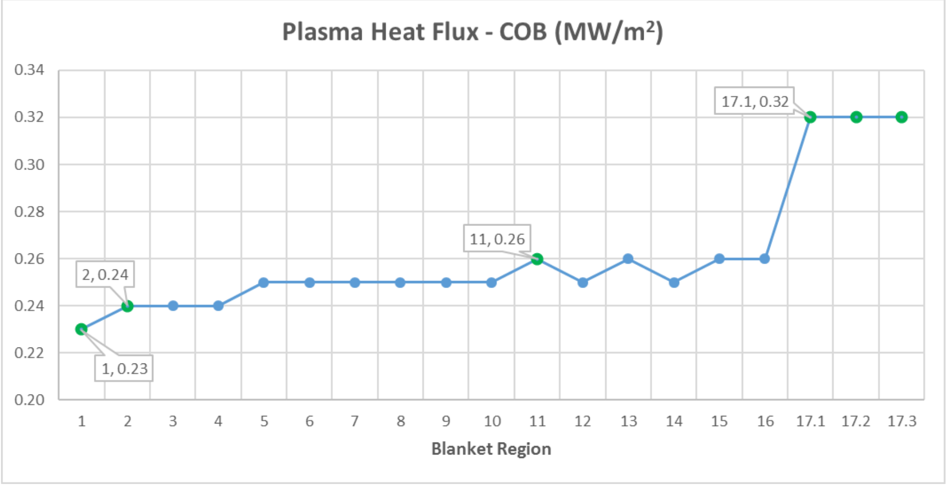
Thermal

Irradiation Swelling

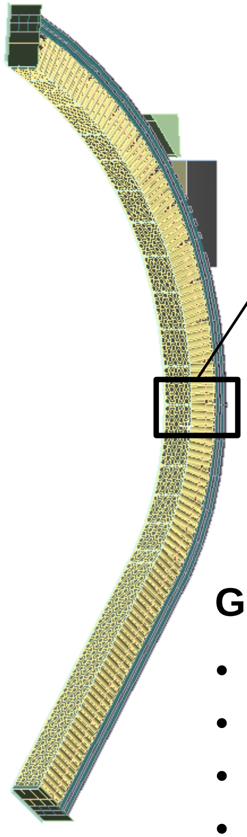
Central Outboard (COB) Segment on Single Module Segment (SMS) Concept

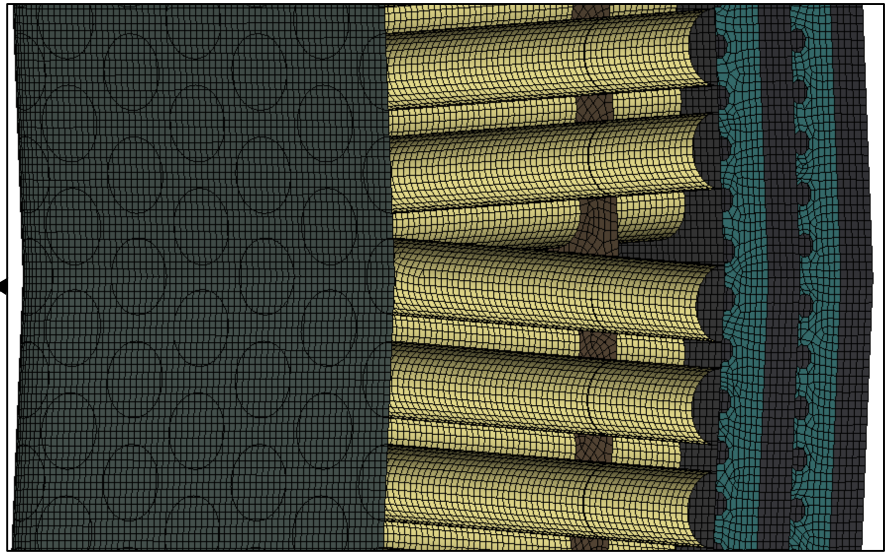






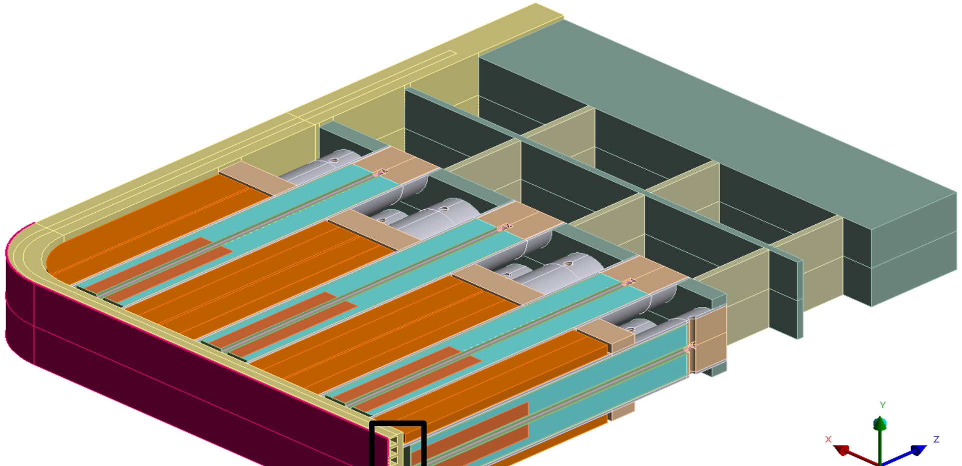
2. Finite Element Modelling: Global and Sub-model

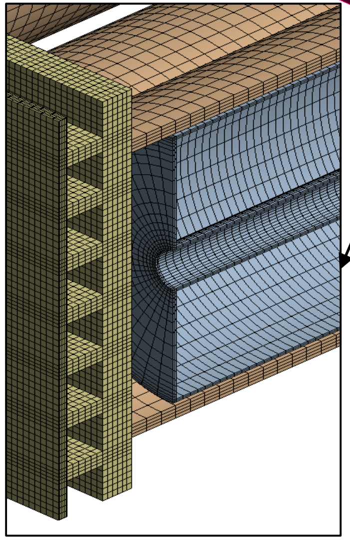




Global Model

- 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

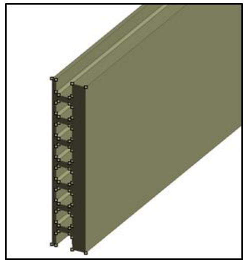


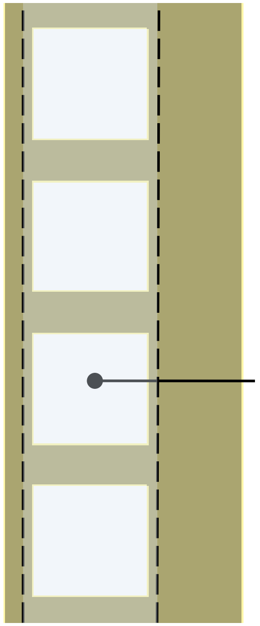


Sub-Model

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

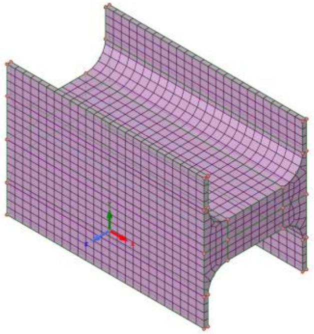
2. Finite Element Modelling: Modelling of first wall





First Wall model

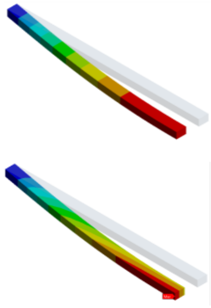
- Trade-off studies between solid, orthotropic shell and layered shell
- Selected 3 layered shell element
- Middle orthotropic layer
- *Ansys Material Designer to* estimate equivalent material properties
- A Representative Volume Element (RVE) is used for the numerical tests



RVE – orthotropic layer

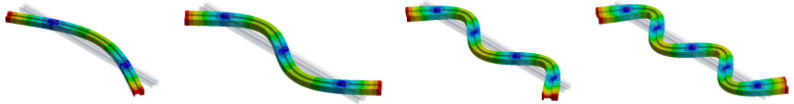
Verification studies: I-beam bending under distributed loading

	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%	-



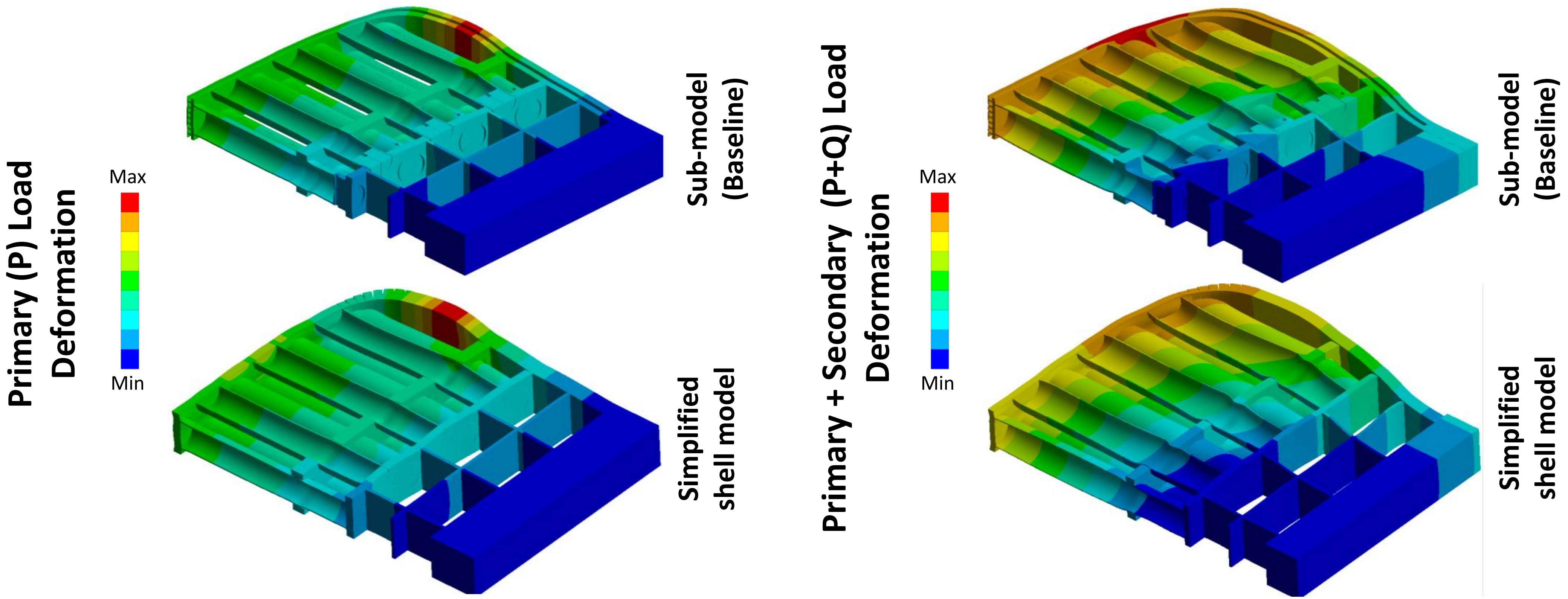
Verification studies: I-beam natural frequencies

	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%



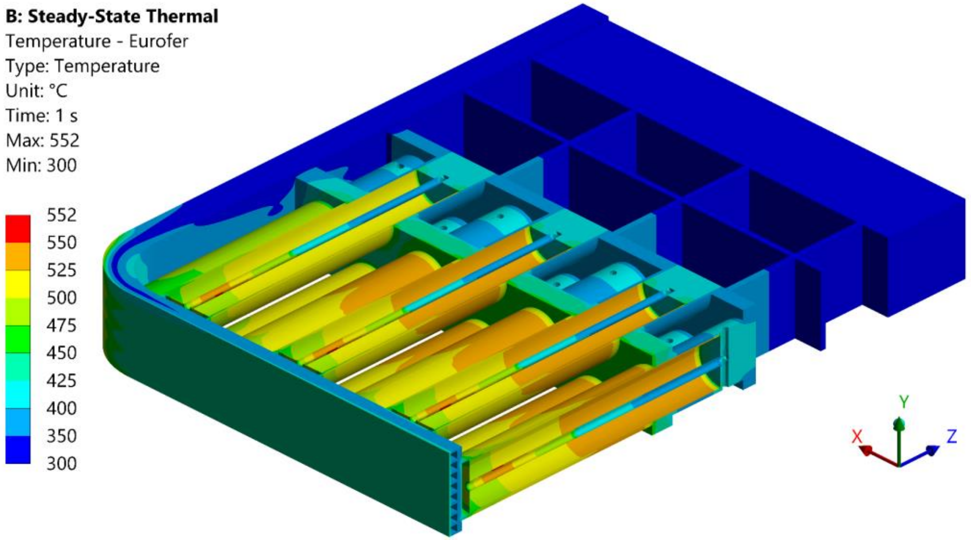
Mode 1 Mode 2 Mode 3 Mode 4

2. Finite Element Modelling: Benchmarking studies



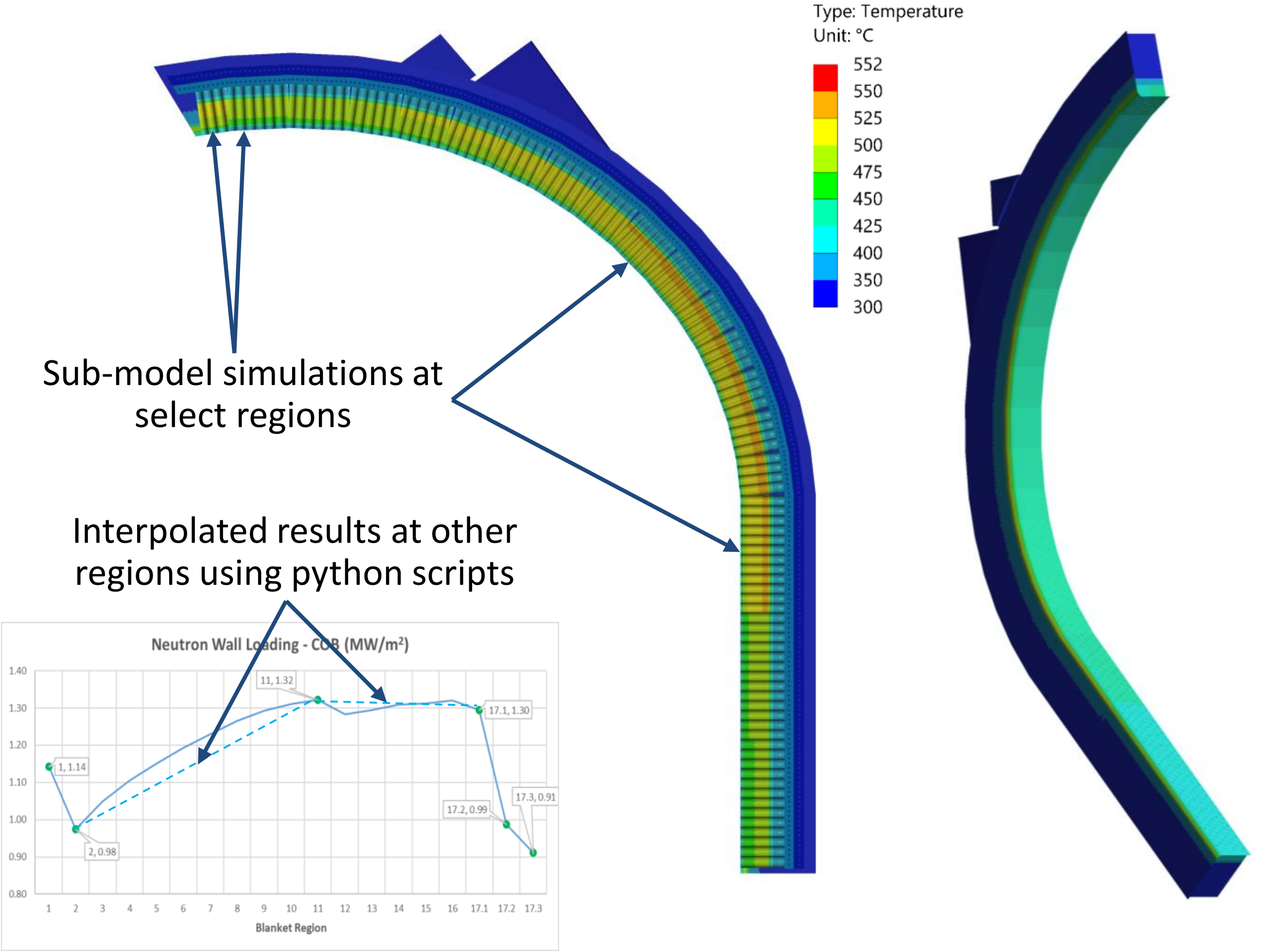
	Elements	Nodes	Avg. Aspect Ratio	Displacement max (mm) P Load	Error Displacement P Load	Displacement max (mm) P+Q Load	Error Displacement P+Q Load
Sub-model (Baseline)	1.5Million	7.1Million	3.8	0.72	NA	5.68	NA
Simplified shell model	16328	17513	1.2	0.73	2.5%	5.30	6.7%

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

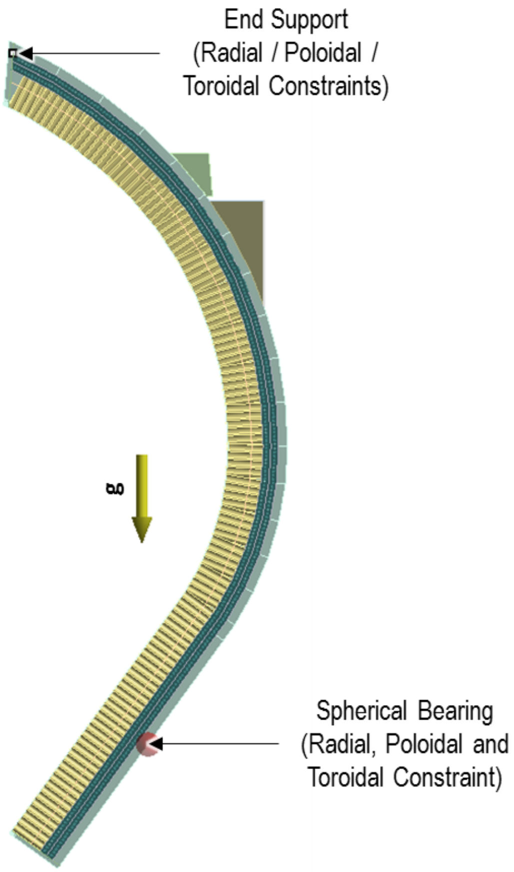


Sub-model simulations at select regions

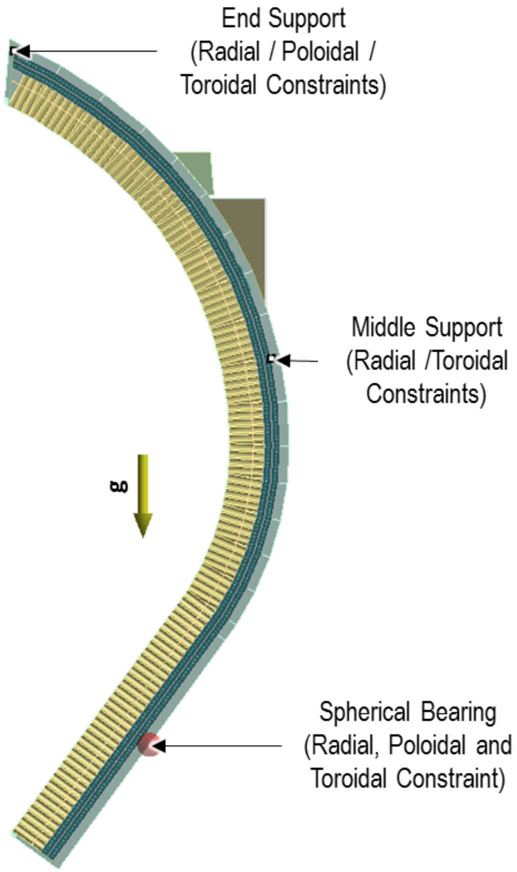
Interpolated results at other regions using python scripts

Temperature Distribution on the Global Model

3. Attachment System



2-Point Support System



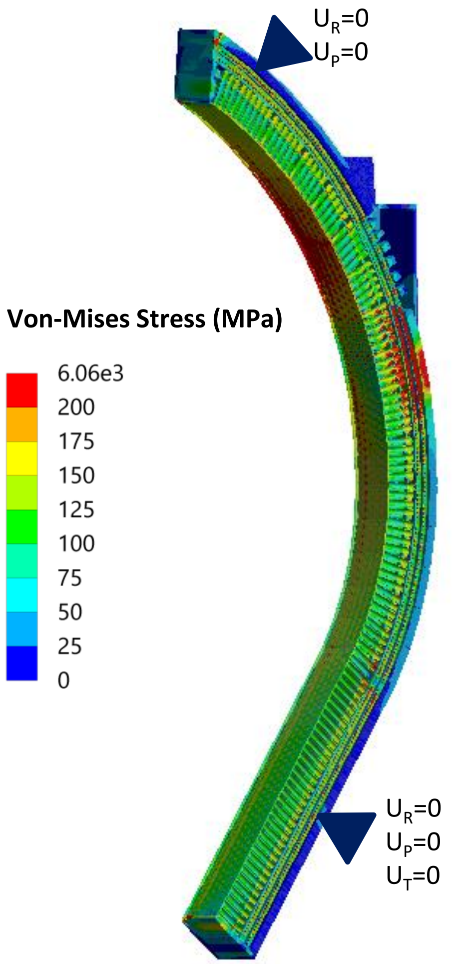
3-Point Support System

Design Requirements

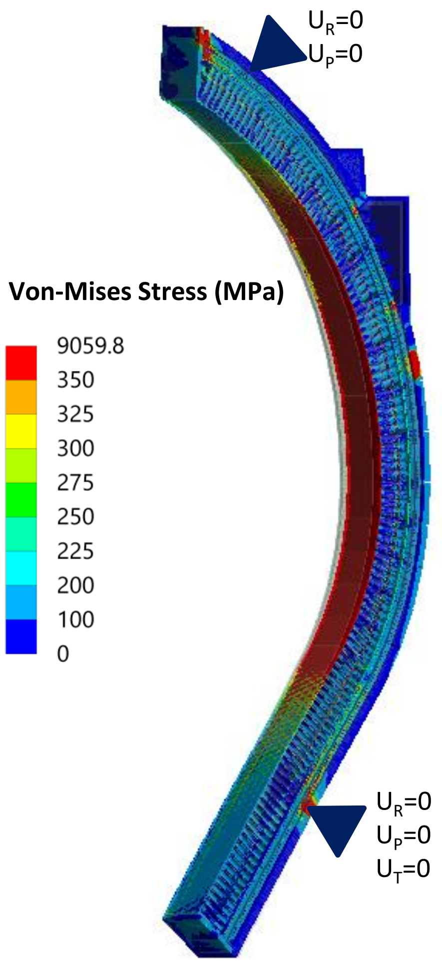
- Support the segments under gravity, pressure & seismic loads
- Minimize thermal stresses
- Support EM Loads during operation
- Avoid contact to vacuum vessel
- Remote handling friendly

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

4. Results



Primary (P) Loading

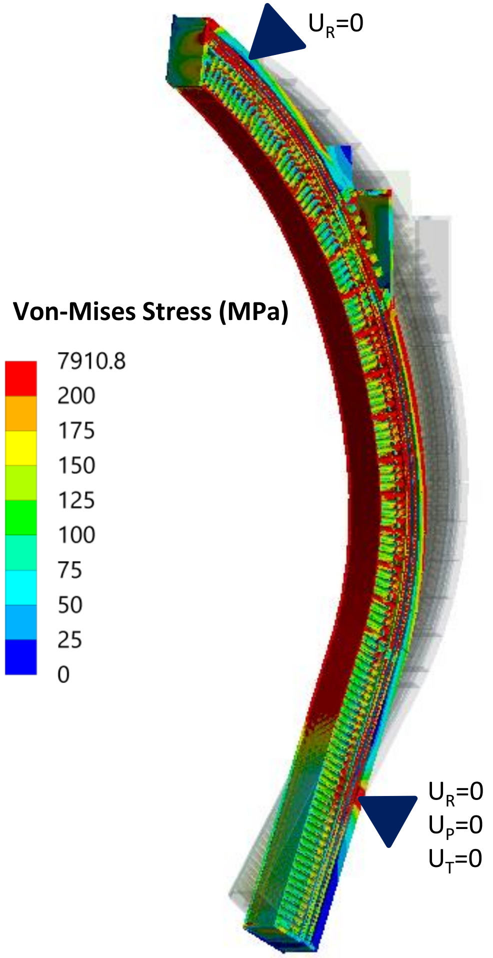


Primary + Secondary (P+Q) Loading

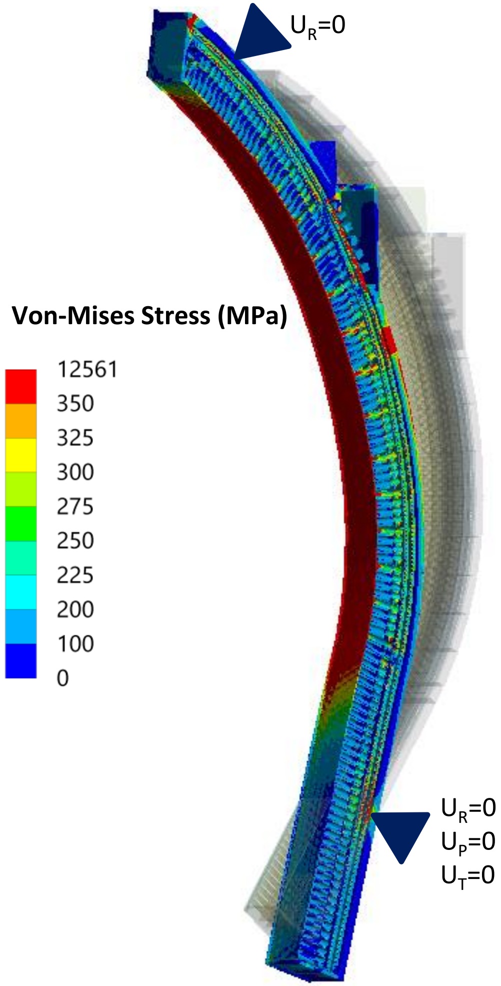
Design Option 1

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

4. Results



Primary (P) Loading

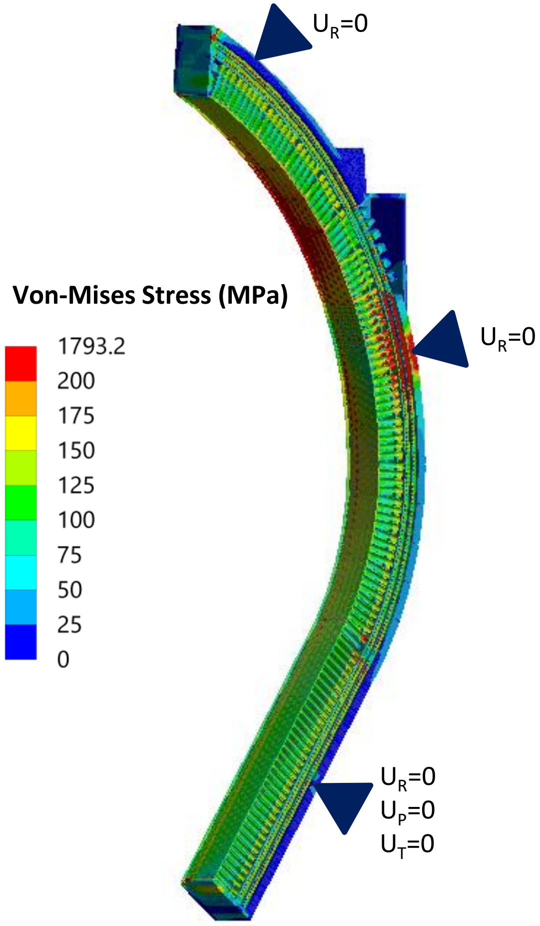


Primary + Secondary (P+Q) Loading

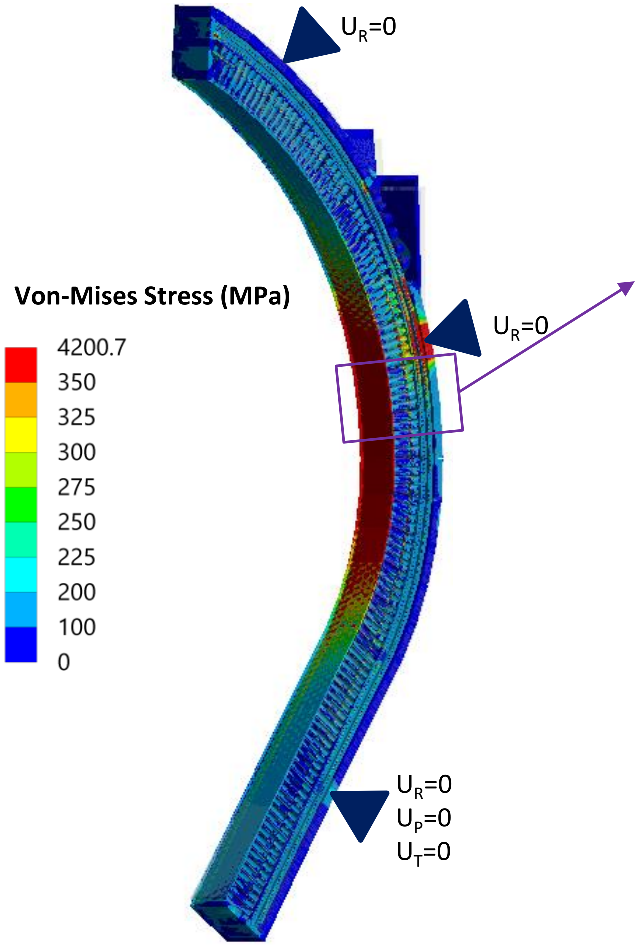
Design Option 2

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

4. Results



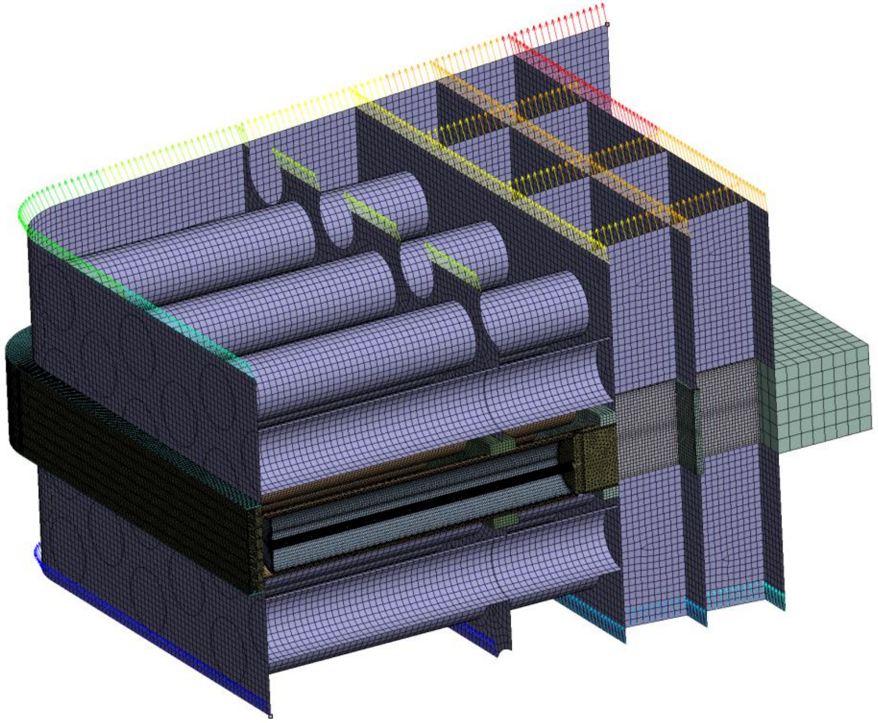
Primary (P) Loading



Primary + Secondary (P+Q) Loading

Design Option 3

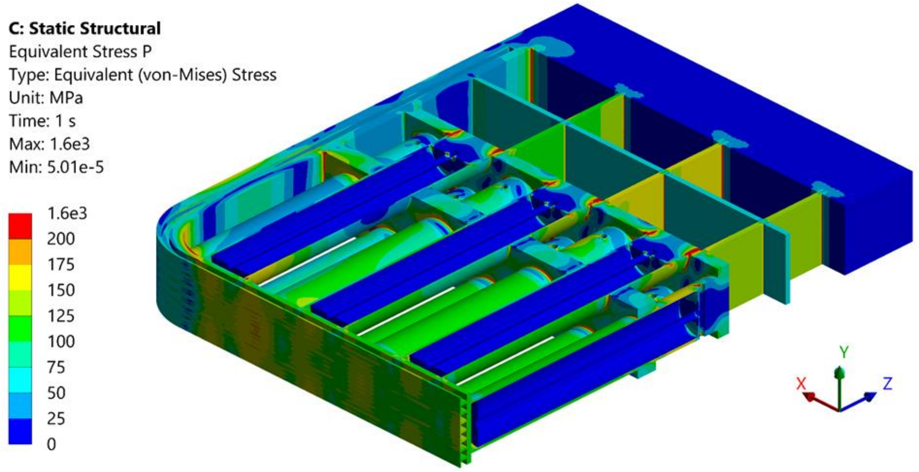
- Supports the assembly well against primary loading
- Secondary thermal stresses are still high – but less than option 1
- Sub-model simulation driven using global displacements at this location



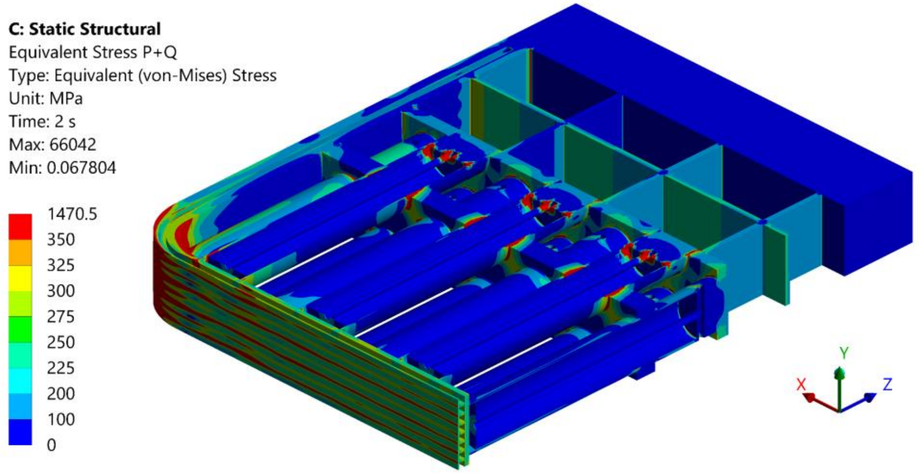
4. Results

Sub-model results under plane strain conditions

Primary (P) Load

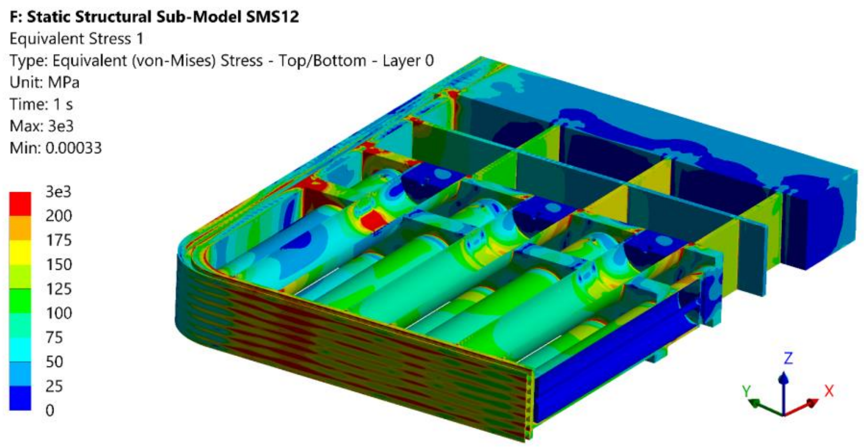

C: Static Structural
Equivalent Stress P
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1 s
Max: 1.6e3
Min: 5.01e-5

Primary + Secondary (P+Q) Load

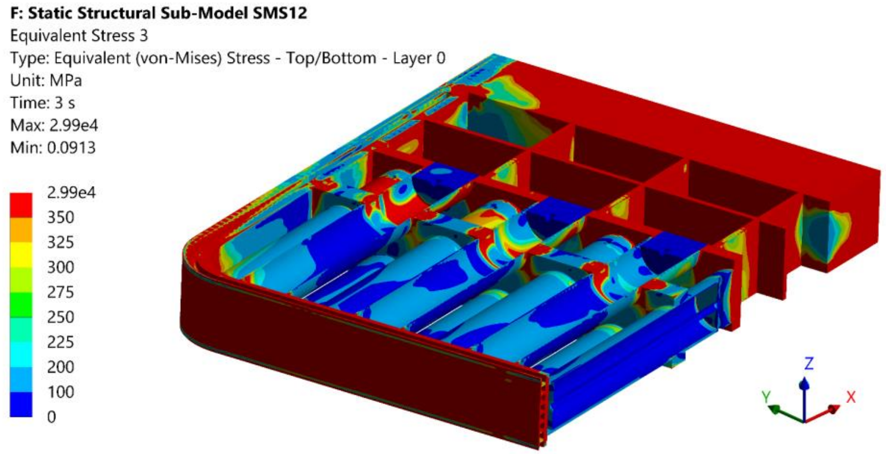

C: Static Structural
Equivalent Stress P+Q
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 2 s
Max: 66042
Min: 0.067804

Sub-model results using global model displacements

Primary (P) Load


F: Static Structural Sub-Model SMS12
Equivalent Stress 1
Type: Equivalent (von-Mises) Stress - Top/Bottom - Layer 0
Unit: MPa
Time: 1 s
Max: 3e3
Min: 0.00033

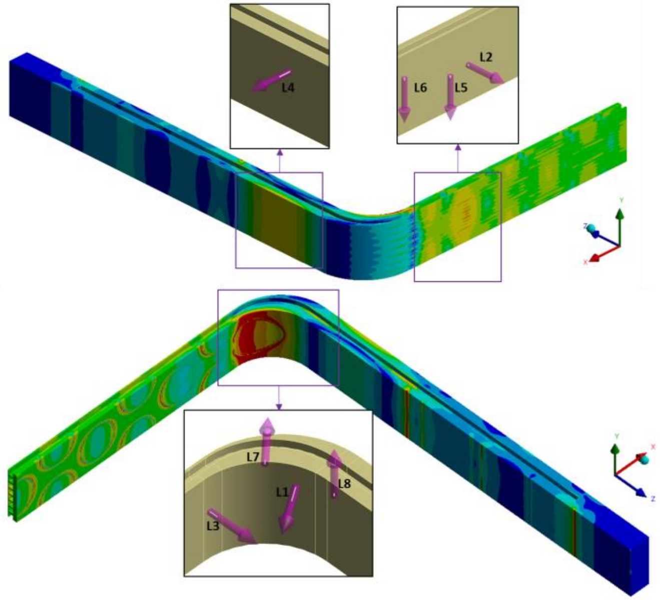
Primary + Secondary (P+Q) Load


F: Static Structural Sub-Model SMS12
Equivalent Stress 3
Type: Equivalent (von-Mises) Stress - Top/Bottom - Layer 0
Unit: MPa
Time: 3 s
Max: 2.99e4
Min: 0.0913

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

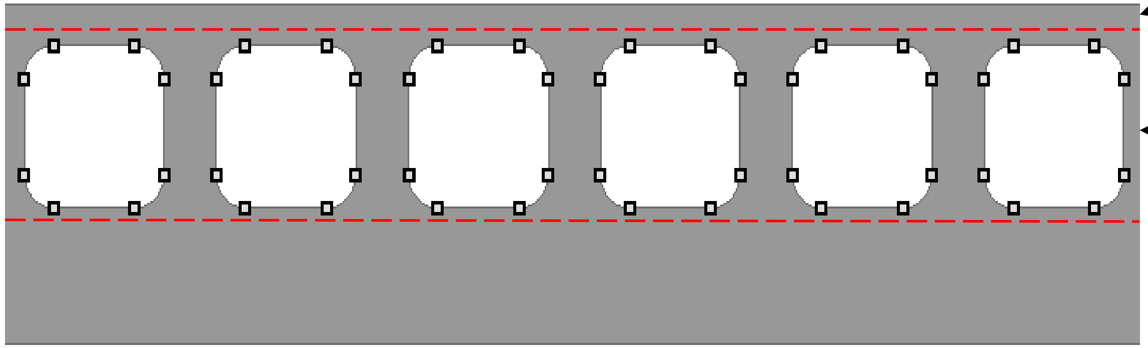
Further work plans:

- 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)

Backup Slides

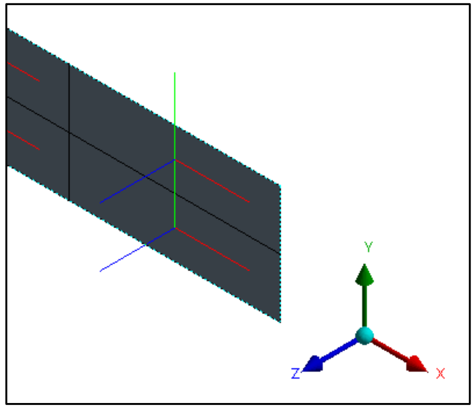
Orthotropic Properties



First Layer
(Isotropic with 2mm thickness)

Second Layer
(Orthotropic with 13mm thickness)

Third Layer
(Isotropic with 10mm thickness)



Eurofer97 Material properties at 20°C

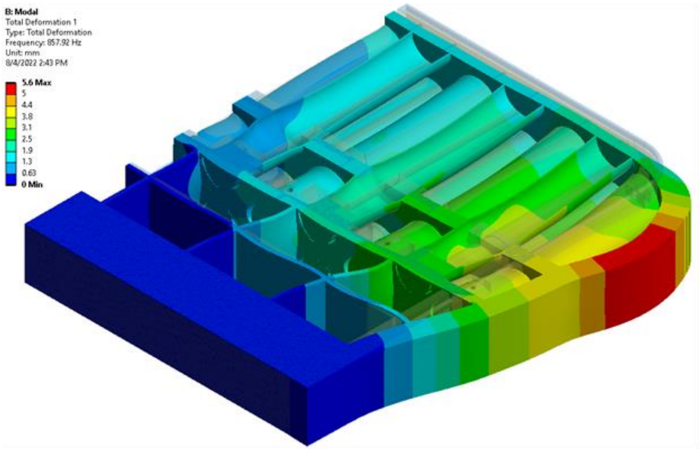
Temperature (°C)	E (GPa)	N	G (GPa)	Density (kg/m^3)
20	217	0.30	83	7760

Orthotropic properties for the middle layer in the layered shell model at 20°C

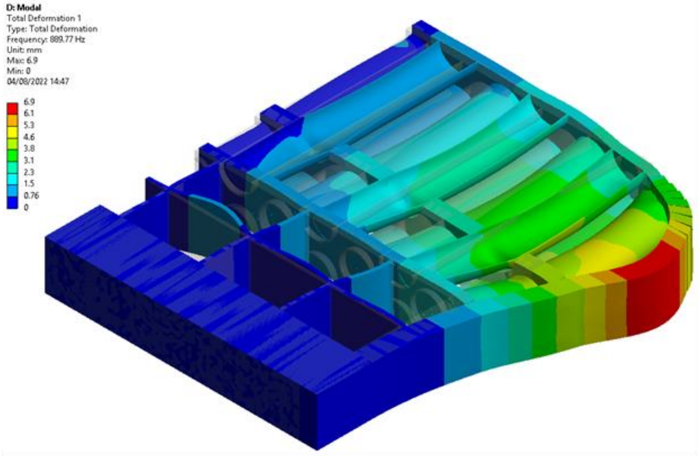
Temperature (°C)	Ex (GPa)	Ey (GPa)	Ez (GPa)	Nxy	Nyz	Nxz	Gxy (GPa)	Gyz (GPa)	Gxz (GPa)	Density (kg/m^3)
20	77	25	63	0.30	0.03	0.30	9.5	0.4	24.4	2745

Note: Density is adjusted to match the solid mass

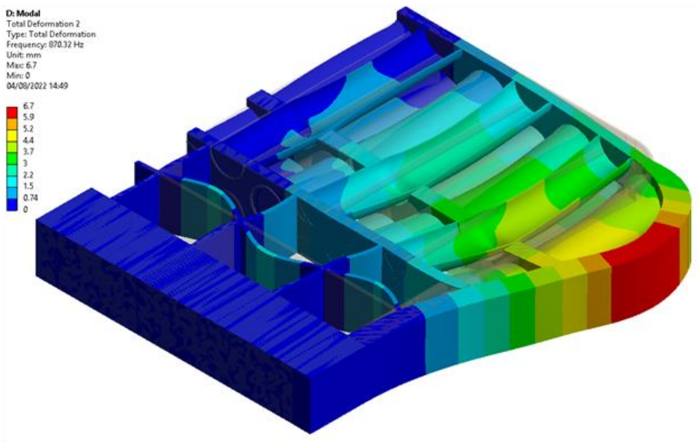
Finite Element Modelling: Modal Analysis benchmarking



FP9 Baseline Model
Mode 1 (858 Hz)



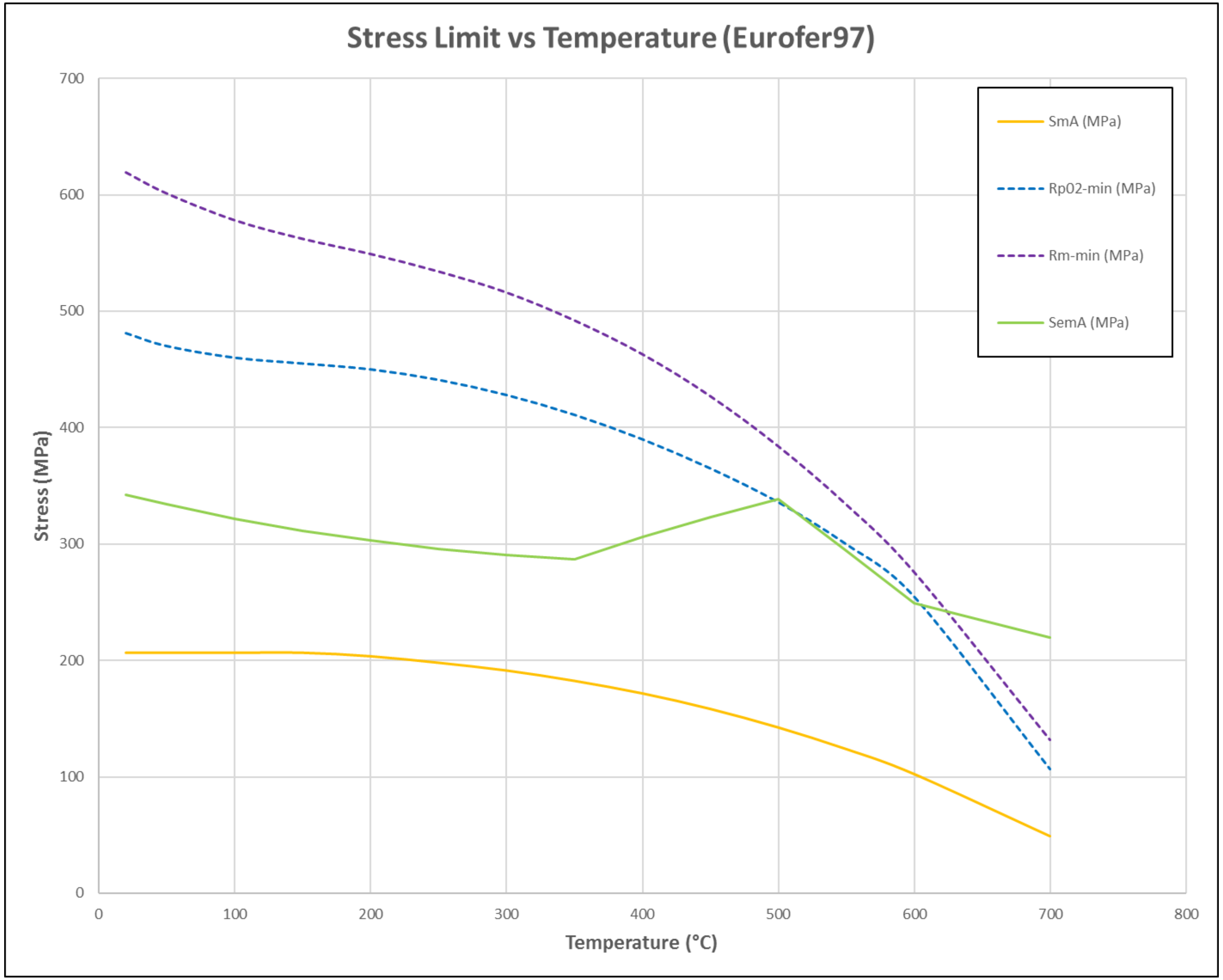
Simplified Shell Model
Mode 1 (890 Hz)



Simplified Solid FW Model
Mode 2 (870 Hz)

	f1 (Hz)	**f2 (Hz)**	**f5 (Hz)**	**Error f1**	**Error f2**	**Error f5**
Sub-model (Baseline)	**858**	**912**	**1154**	**NA**	**NA**	**NA**
Shell Model	890	949	1237	4%	4%	7%
Shell model with Solid FW	870	942	1242	1%	3%	8%

Eurofer97 Elastic Assessment Stress Limits



Plastic Collapse:

$$\overline{P_m} \leq S_m$$

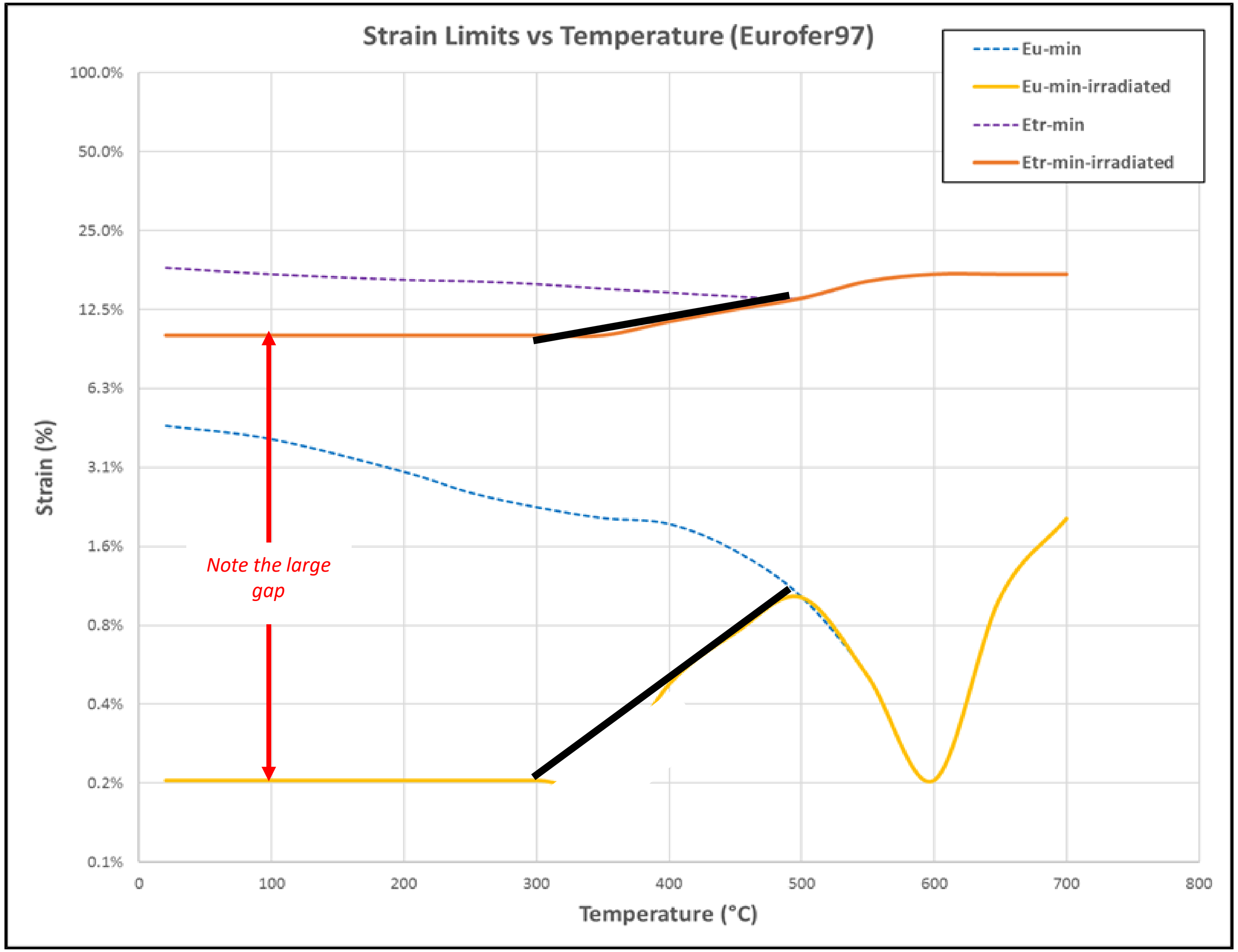
Plastic Instability:

$$\overline{P_L + P_B} \leq 1.5 \times S_m$$

Plastic flow localization:

$$\overline{P_L + Q_L} \leq S_{em}$$

Eurofer97 Strain Limits for Inelastic Assessment



Plastic flow localization:

$$(\tilde{\varepsilon}_m)_{pl} \le \frac{\varepsilon_u(T_m, \Phi t_m)}{2}(SDC - IC)$$

Exhaustion of ductility:

$$(\tilde{\varepsilon})_{pl} \le \frac{\varepsilon_{tr}(T, \Phi t)}{TF}(SDC - IC)$$