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Structural Analysis of a HCPB Blanket for DEMO Reactor

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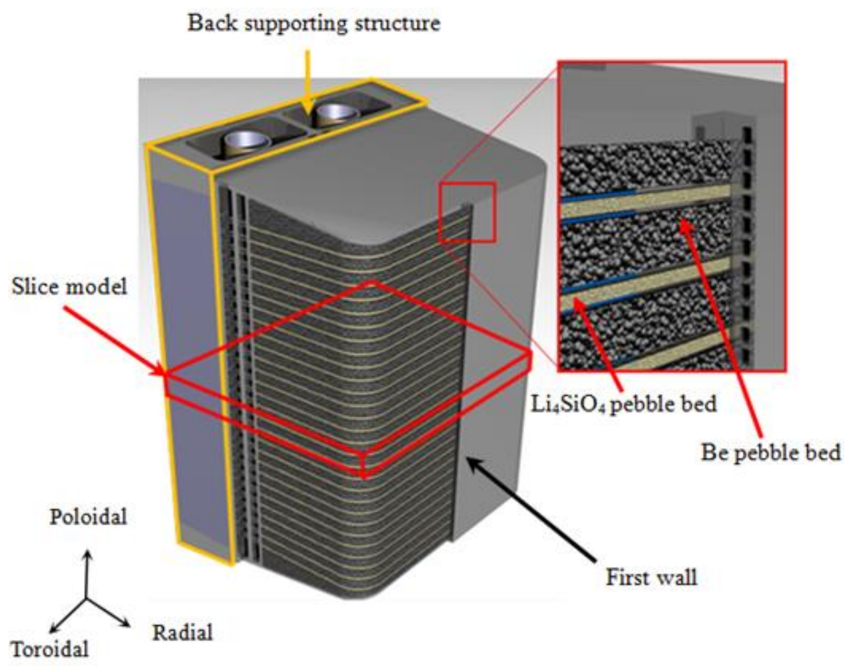
Introduction

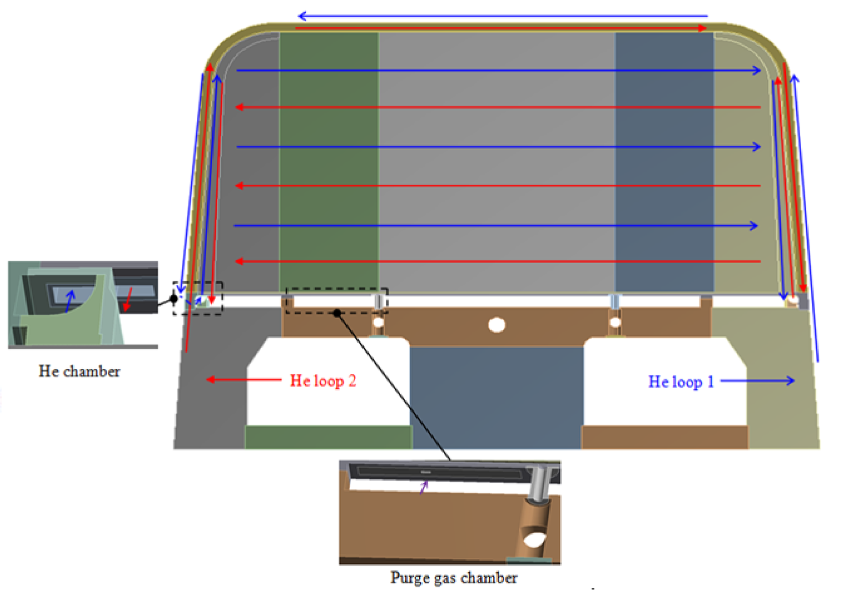
- A 3D slice model of the HCPB DEMO blanket has been set up to run thermo-mechanical analyses under steady state and DEMO transient pulsed conditions.
- From these analyses critical time points have been identified in which the stresses are higher, and for each of these time points a complete thermo-mechanical assessment has been conducted.
- The results have been assessed with respect to the design codes (mainly RCC-MR, completed by SDC-IC).

Finite Element Model

Geometry



HCPB DEMO Blanket



3D Slice Model
Totally, 855688 elements, 4208964 nodes

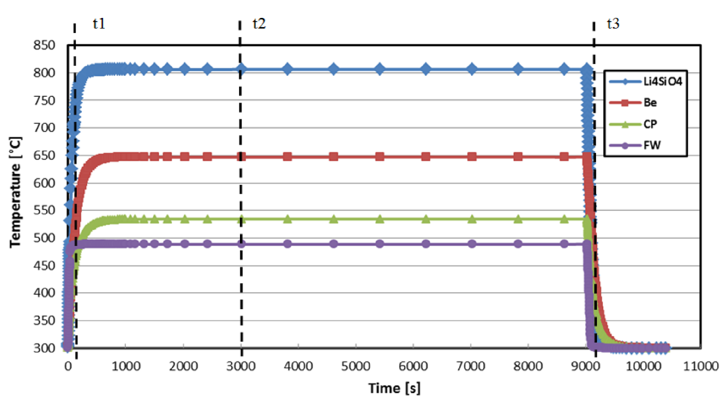
Loads

Thermal and mechanical loads during normal operation have been considered here.

During pulsed operation, thermal loads follow the plasma pulse evolution, while mechanical loads remain constant.

Loads are listed as follows:

- Internal pressure on cooling channels and in the manifold equal to 8 MPa, operating pressure of helium coolant loop;
- Internal pressure on surfaces in contact with the purge gas equal to 0.2 MPa, operating pressure of purge gas loop;
- Temperature field imported by thermal analyses performed before;
- t1=30s, the instant where the maximum temperature on the FW reaches stationary level while other sub-components still "cold";
- t2=3000s, the instant where temperatures on all sub-components can be considered at asymptotic conditions (steady-state level);
- t3=9157s, the instant where the inversion of the temperature difference between FW and breeding zone is maximum;
- For each of these time instants, a separate thermo-mechanical analysis has been done considering the previously calculated thermal profiles.



Maximum temperature evolutions following plasma pulse

Boundary condition

Bottom surfaces of the model are considered as symmetry planes;

Top surfaces are coupled poloidally to move in parallel;

One node is fixed at radial direction, another node fixed at radial and toroidal direction to prevent rotation.

Reference Design Codes and Rules

Main reference design code used is the French code RCC-MR, completed by the SDC-IC to take into account the effects of neutron irradiation.

The "SF1" category condition Level A criteria assigned to the nominal loading case is considered in this study.

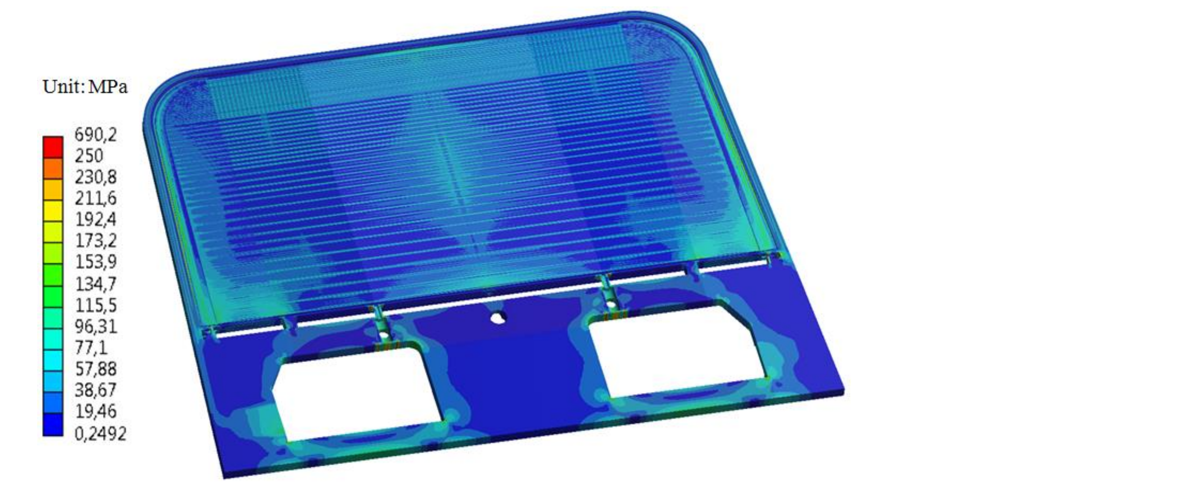
The damage modes considered in this investigation are listed as follows:

(a) Immediate plastic collapse and plastic instability (IPC&IPI)
(b) Immediate plastic flow localization (IPFL)
(c) Immediate local fracture due to exhaustion of ductility (ILF)
(d) Thermal creep
(e) Ratcheting
(f) Fatigue

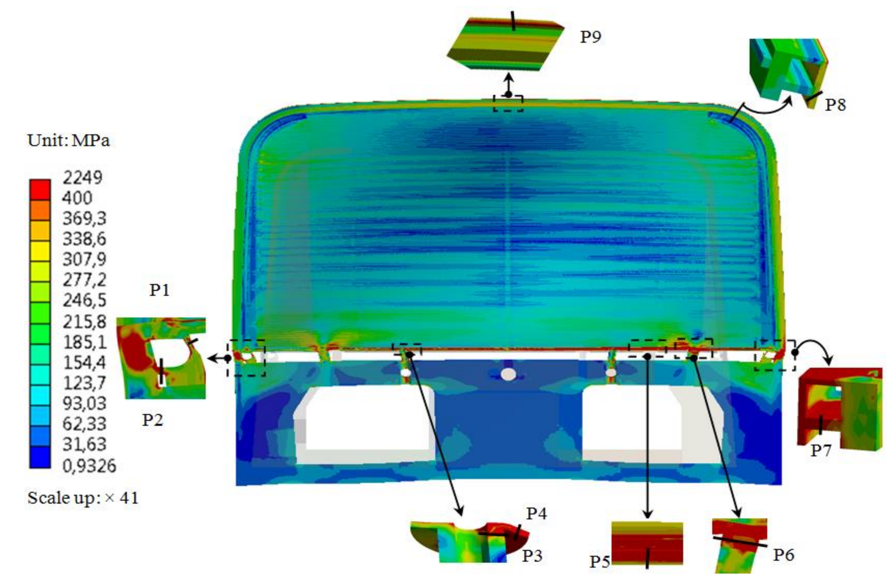
The procedure to assess the thermo-mechanical loadings is based on the linearization of the stress tensor on a path defined along the thickness of a region where von Mises stress is the highest.

Thermal profiles is used here to calculate the mean temperature of the defined path, as we need the mean temperature to obtain allowable stresses along the path.

Results and Analyses



Primary von Mises stresses on blanket structure



Primary plus secondary von Mises stress field on blanket structure and paths for linearization

Assessment of monotonic type damages

Table 1. Values of the criteria against IPC&IPI and IPFL damage modes (in [MPa])

Path	IPC&IPI $\overline{P_m}$			IPC&IPI $\overline{P_L+P_b}$			IPFL $\overline{P_L+Q_L}$		
	Value	Limit	Margin	Value	Limit	Margin	Value	Limit	Margin
P1	138.6	175.8	21%	150.0	263.7	43%	371.5	207.5	-79%
P2	32.2	178.4	82%	53.0	267.6	80%	590.1	226.9	-160%
P3	23.3	186.2	87%	40.5	279.3	85%	413.9	196.2	-111%
P4	35.9	186.2	81%	100.1	279.3	64%	511.4	196.2	-161%
P5	5.4	147.4	96%	6.1	221.1	97%	384.3	314.6	-22%
P6	7.9	146.3	95%	31.9	219.5	85%	430.2	317.1	-36%
P7	54.0	180.4	70%	55.3	270.6	80%	574.8	219.4	-162%
P8	24.0	151.0	84%	49.9	226.5	78%	356.3	306.3	-16%
P9	9.9	154.4	94%	56.8	231.6	75%	368.8	298.0	-24%

A global satisfying behavior for immediate plastic collapse and plastic instability damage modes, and thermal creep damage mode;

Fail to fulfil the criteria to prevent immediate plastic flow localization damage mode in some regions;

High thermal gradients are main drivers for not satisfying the immediate plastic flow localization damage mode.

Table 2. Values of the criteria against thermal creep (in [MPa])

Path	Starter blanket $\overline{P_m}$			Starter blanket $\overline{P_L+P_b/K_t}$			Second blanket $\overline{P_m}$			Second blanket $\overline{P_L+P_b/K_t}$		
	Value	Limit	Margin	Value	Limit	Margin	Value	Limit	Margin	Value	Limit	Margin
P1	138.6	235.5	41%	148.2	235.5	37%	138.6	229.4	40%	148.2	229.4	35%
P2	32.2	244.5	87%	50.1	244.5	80%	32.2	238.5	86%	50.1	238.5	79%
P3	23.3	274.5	92%	38.0	274.5	86%	23.3	269.0	91%	38.0	269.0	86%
P4	35.9	274.5	87%	92.2	274.5	66%	35.9	269.0	87%	92.2	269.0	66%
P5	5.4	158.5	97%	5.9	158.5	96%	5.4	151.0	96%	5.9	151.0	96%
P6	7.9	156.1	95%	27.5	156.1	82%	7.9	148.5	95%	27.5	148.5	81%
P7	54.0	251.8	79%	53.7	251.8	79%	54.0	245.9	78%	53.7	245.9	78%
P8	24.0	166.6	86%	47.7	166.6	71%	24.0	159.2	85%	47.7	159.2	70%
P9	9.9	174.7	94%	47.6	174.7	73%	9.9	167.5	94%	47.6	167.5	72%

Counter-actions:

Increase the thickness of the weak parts;

Decrease temperature difference between components.

Assessment of cyclic type damages

Table 3. Values of the criteria against ratcheting damage mode (in [MPa])

Path	Ratcheting $(t_1:t_2)$			Ratcheting $(t_1:t_3)$			Ratcheting $(t_2:t_3)$		
	Value	Limit	Margin	Value	Limit	Margin	Value	Limit	Margin
P1	633.8	527.4	-20%	423.8	527.4	20%	392.9	527.4	26%
P2	887.1	535.2	-66%	400.1	535.2	25%	588.0	535.2	-10%
P3	557.3	558.6	0.1%	630.6	558.6	-13%	242.7	558.6	57%
P4	724.6	558.6	-30%	1040.9	558.6	-86%	731.1	558.6	-31%
P5	422.9	442.2	4%	306.6	442.2	31%	126.7	442.2	71%
P6	440.6	438.9	-0.4%	368.5	438.9	16%	159.8	438.9	64%
P7	663.1	541.2	-23%	264.3	541.2	51%	511.4	541.2	6%
P8	187.1	453	59%	377.0	453	17%	375.8	453	17%
P9	305.4	463.2	34%	273.7	463.2	41%	248.5	463.2	46%

The FW (P8 and P9) fulfils the ratcheting during plasma ramp-up and ramp-down phases.

Some regions cannot satisfy the ratcheting damage, after implementing the counter-actions presented above, the problems will probably be eliminated.

Table 4. Cycle number against fatigue damage mode (in [MPa])

Path	Cycles: Fatigue $(t_1:t_2)$	Fatigue $(t_1:t_3)$	Fatigue $(t_2:t_3)$
P1	9	∞	∞
P2	<5	∞	17
P3	<5	<5	∞
P4	∞	<5	∞
P5	21	688205	∞
P6	20	8291	∞
P7	<5	∞	1012
P8	∞	∞	∞
P9	∞	∞	∞

Here ∞ means > 1×10^6

FW shows in general a satisfying behavior against fatigue damage.

Critical are regions at the connection between different massive structures or at pipes penetrations.

These regions are in general the same ones identified as weak by the ratcheting analysis.

Design improvement at these regions to tackle the problems is needed.

Conclusions

The blanket structure shows a global satisfying behavior for immediate plastic collapse and plastic instability damage modes, and thermal creep damage mode.

The blanket fails to fulfil the criteria to prevent immediate plastic flow localization damage mode in some regions.

Counter-actions proposed are: reducing the thermal gradients and increasing the thickness along the linearization paths.

FW shows a satisfying behavior against ratcheting and fatigue damage modes during plasma ramp-up and ramp-down phases.

Especially localized regions at the connection between massive structure or at pipe penetration showed unsatisfactory performances against ratcheting and fatigue damage modes; here design improvements are needed.

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