Design of the European DEMO vacuum vessel inboard wall

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A R T I C L E I N F O

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A B S T R A C T

The pre-concept design of the DEMO Vacuum Vessel is going on in view of the 2020 gate review; moreover the nuclear heat loads on the vessel inner shell were determined and found to be about one order of magnitude higher compared to ITER. A subsequent thermal-structural analysis of the vessel inner shell revealed high thermal stresses and a large temperature gradient through the inner shell thickness. Given the simultaneous occurrence of primary membrane stresses in the entire vessel inboard wall and, in proximity of the vessel ribs, high bending stresses due to the coolant pressure, a survey of all options within the design rules was required to identify the inter-dependencies of the individual stress limits (primary membrane, primary bending, thermal membrane plus bending). In order to face this kind of issues a detailed assessment on the design of the inboard wall of DEMO Vacuum Vessel has been conducted and is presented here. The current work evaluates both P and S type damages for the inboard wall of DEMO Vacuum Vessel in case of high nuclear heat load, vacuum vessel coolant pressure and toroidal field coil fast discharge. The elastic analysis method has been used to check the rules for prevention of both types of damage. The rules applied to prevent the aforementioned damages are compliant to Level A criteria, in case of negligible creep and negligible irradiation. In order to check the structural integrity of the inboard wall of DEMO VV against high thermal and mechanical loads, optimization structural analyses were performed and checked against the rules provided in the applicable design code (RCC MRx).

1. Introduction

The first design of the DEMO Vacuum Vessel (VV) has been developed and structurally verified in previous studies [1], moreover the nuclear heat loads on the vessel inner shell were determined and found to be about one order of magnitude higher compared to ITER [2]. A subsequent thermal-structural analysis of the vessel inner shell revealed high thermal stresses (~1.5Sm) and a large temperature gradient (~50 K) through the inner shell thickness [3]. Given the simultaneous occurrence of primary membrane stresses in the entire vessel inboard wall [4] and, in proximity of the vessel ribs, high bending stresses due to the coolant pressure, a survey of all options within the design rules was required to identify the inter-dependencies of the individual stress limits (primary membrane, primary bending, thermal membrane + bending). A detailed assessment on the design of the inboard wall of DEMO VV has been conducted. According to RCC MRx (2012) two types of damage shall be evaluated to verify the structural integrity of the DEMO Vacuum Vessel [5]:

- P type damage
- S type damage

Previous studies address the structural integrity of the DEMO Vacuum Vessel evaluating the P type damage in case of Vertical Displacement Event [6,7]. The current work evaluates both the P and S type damages for the inboard wall of DEMO VV in case of high nuclear heat load, vacuum vessel coolant pressure and toroidal field coils fast discharge (TFCFD) radial pressure. The elastic analysis method has been used to check the rules for prevention of both types of damage. Level A criteria are applied for the in case of negligible creep and negligible irradiation.

A set of finite element analyses was run modelling a single slice of a half sector of the DEMO VV inboard wall.

2. Design of vacuum vessel inboard wall

Based on the DEMO reference configuration a parametric model of a

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thin slice of a half inboard sector (10°) has been developed (Fig. 1) with a small vertical extension of only 10 mm, since loads and boundary conditions are approximately constant along the vertical axis of DEMO machine.

The dimension and geometrical parameters set for the modelling are the following (Fig. 2):

- Inner shell thickness: $\mathbf{T_{is}}$
- Outer shell thickness: $\mathbf{T_{os}}$
- Lateral rib thickness: $\mathbf{T_{lrib}}$
- Central rib half thickness: $\mathbf{HT_{crib}}$
- Number of ribs: $\mathbf{N_{rib}}$

3. Structural integrity assessment

The assessment was structured in two main steps. In the first one a set of configurations has been defined varying the parameters related to the load conditions. In the second step, assuming the load scheme outcomes of the first phase, a set of geometrical parameters have been optimized.

The elastic analysis method has been used and the AISI 316 L(N) has been assumed as material of the Inboard Wall [5]. The material type property values were defined for the operating temperature (200 °C) [8]. A parametric FEM model of the inboard Wall slice has been provided to run the optimization analysis (Fig. 3). Its main characteristics are listed in (Table 1).

3.1. Loads and boundary condition

Since a single sector of DEMO VV and its load scheme are symmetric with to respect to the poloidal mid-plane and to the extremity plane of each sector, only half DEMO VV inboard wall has been modelled. Symmetry boundary conditions have been applied on the planes highlighted in Fig. 4. The vertical displacements have been constrained.

During normal operation the inboard wall of DEMO VV is subjected to a coolant pressure, a radial pressure due to TFCFD and nuclear heat loads according to the following qualitative diagram (Fig. 5).

The loads have been parametrized in order to assess the values that minimize the induced stresses inside the wall.

3.1.1. Coolant pressure

Two different coolant pressure values have been chosen as reference for the present assessment since the VV operating temperature had not been defined at the time of writing this article (1 MPa and 3.15 MPa) [8]. The cooling convection coefficient is assumed to be 0.5 kW/(m^2K), based on the CFD analysis of the ITER VV regular sector #5 [9].

3.1.2. Radial pressure of toroidal field coils fast discharge

Upon detection of a thermal quench the current in the TF coils is discharged over the dump resistors. Consequently, a poloidal current is induced in the vessel wall. In the initial phase of the discharge when the toroidal field is still present the TFCFD causes a significant outward pressure on the VV wall. This load has assumed as primary. The induced

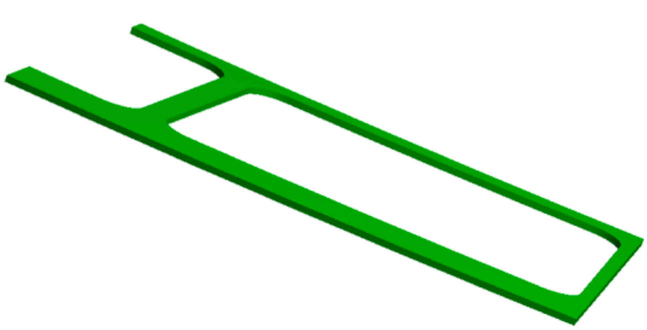

Fig. 1. Slice of DEMO VV inboard wall as analysed by finite element method.

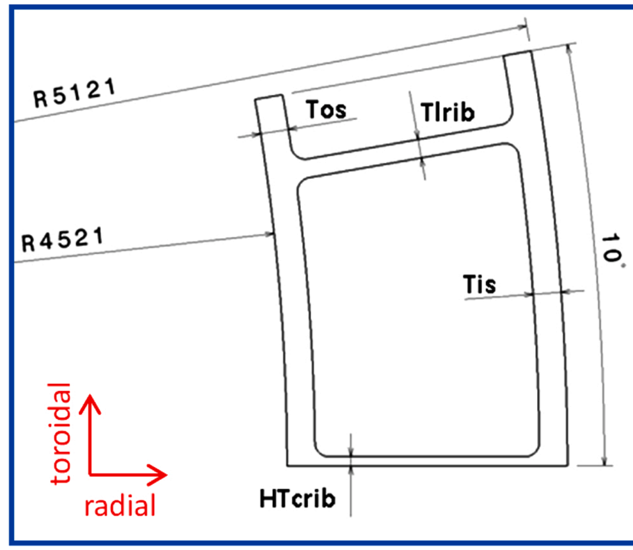

Fig. 2. Main dimensions and parameters of DEMO VV half sector inboard wall.

current scales linearly with VV shell thickness and discharge time constant (reducing with increasing time constant), the PTFCFD radial pressure was assumed to be a function from inner shell thickness.

The equivalent time constant of the current decay of the TF coil shall not be smaller than 27 s [8]. Previous studies calculated the TFCFD radial pressure on the inner shell of VV inboard wall assuming the VV inboard wall shell with a thickness of 0.06 m. The results of these studies showed that the TFCFD radial pressure acting on VV inboard wall is 0.9 MPa (the value is scaled with respect to the changed quench time constant) [10].

The TFCFD radial pressure, P_{TFCFD}, is defined by the followings relations [11]

$$P_{TFCFD} = \frac{TFCFD_{constant}}{T_{Inner\ shell}}$$

$$TFCFD_{constant} = 0.9\ MPa \cdot 0.06\ m = 0.054\ MPa \cdot m$$

Three different values of $TFCFD_{constant}$ have been considered as reference values for the assessment (0.054, 0.084, 0.114 MPa·m). The TFCFD radial pressure has been applied on the inner surface of both inboard wall shells (inner and outer). A fast discharge of TF coils is defined as a category II event and a Level A Criteria shall be applied [8].

Nuclear Heat load

The nuclear heat load in the inner shell behind the center of the blanket is distributed according to the following function [2]:

$$H(u) = 1.2 \cdot H_{base} \cdot e^{-\left(\frac{u-1}{11}\right)^{0.5} \cdot \ln(1.2)}$$

Where:

$$H_{base}(x) = H_{base\_constant} \cdot e^{-\alpha x}$$

✓ x [cm] is the radial depth in the inner shell from the inner shell plasma-facing surface

✓ α [cm^{-1}] is equal to 0.12.

✓ u [cm] is the distance from the center of a gap between two inboard Breeding Blanket segments.

The decay of nuclear heating H from the center of a gap in toroidal direction (peaking factor 1.2) is a function of the distance u from the center of the gap (Fig. 6.).

Three different values of $H_{base\_constant}$ have been chosen as reference for the assessment (0.4, 0.85, 0.95, 0.105 W/cm^3).

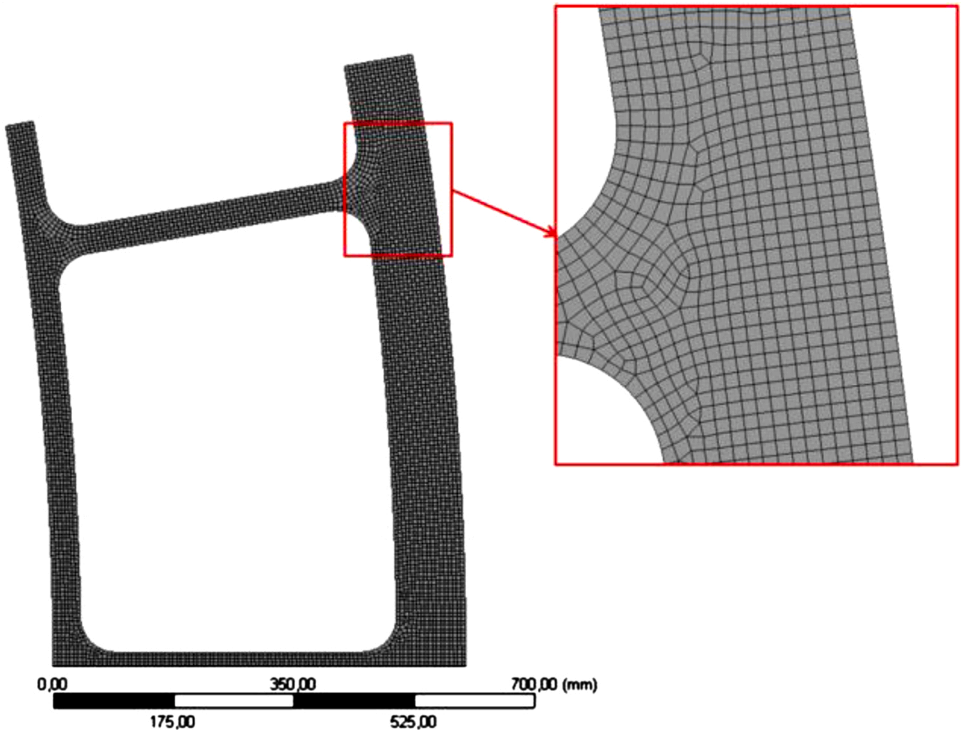

Fig. 3. DEMO VV Inboard Wall Mesh.

Table 1
FEM model characteristics.

Element Type	Solid 186
Number of elements	8724
Number of nodes	51.454
Material type	AISI 316 L(N)

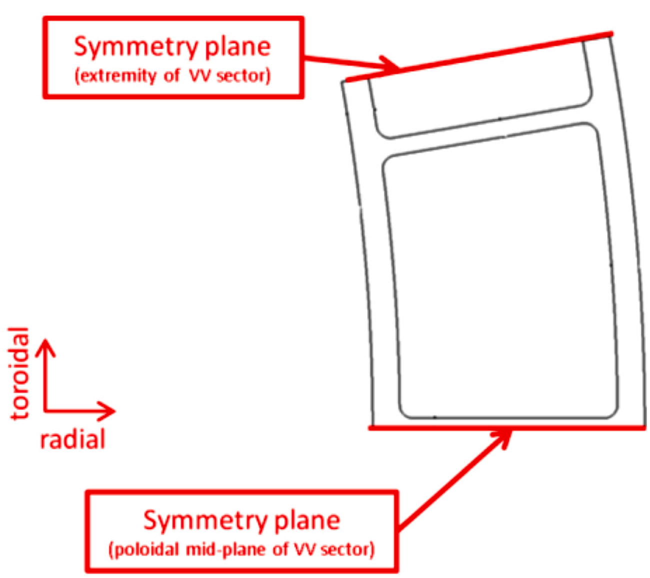

Fig. 4. Boundary Conditions.

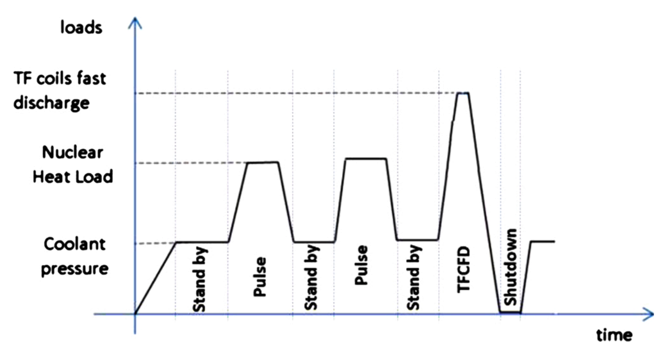

Fig. 5. Qualitative loads distribution in Normal Operation.

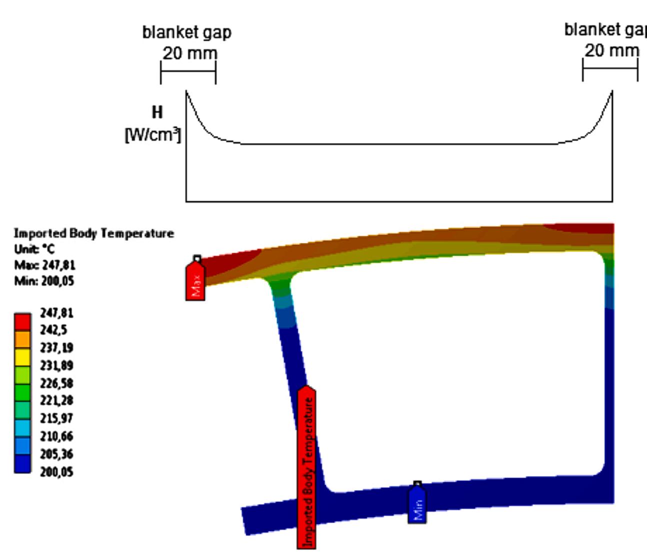

Fig. 6. Heat load distribution along the inner shell.

4. Results and design criteria

In order to check the structural integrity of the VV inboard wall 23 different configurations have been analyzed. The configurations are different both in terms of loads applied and geometrical parameters. Stress linearization has been carried out along the most critical paths according to RB 3324.31. Two different paths have been identified as critical, named “path1″ and “path2″.

As requested to the RCC-MRx code for each configuration both P and S damage have been checked.

4.1. P damage prevention

The first step in the verification of the structural integrity of DEMO VV Inboard Wall consisted in the prevention of P type damage according to the RCC MRx rules. Type P damages are those which can result from the application to a structure of a steadily and regularly increasing loading or a constant loading. According to RCC-MRx [5], the maximum allowable stress shall be:

$$S_m(200^{\circ}) = 130MPa$$

Primary membrane stress and primary membrane plus bending stress have been verified according to RB 3251.112. The configurations highlighted in Table 2, on path1, do not satisfy the P-damage rules. They are mainly those configurations simultaneously combination of the maximum coolant pressure and the minimum shell thickness.

4.2. S damage prevention

Type “S damages” are those which can only result from repeated application of loadings [5]. The nuclear code provides a set of rules to check the component subjected to a repeated loading. Elastic analyses have been performed to evaluate the “S damage” in case of Level A criteria, negligible irradiation and negligible creep. In these cases, the RCC-MRx RB3260 [5] provides different rules to be applied depending from the presence or not of an overload of short duration. For each condition the rules distinguish periods with or without secondary membrane stress. Fig. 8 provides a summary of the rules considered. As worst case the TFCFD has been considered as an overload of short duration and in the case of operating period with secondary membrane stress the RB 3261.1113 has been used to check the structural integrity for prevention of S type damage (Fig. 8).

In this case, the values of Max(σ_m), Max($\sigma_L + \sigma_b$) and Δq, needed for the evaluation of the efficiency index and of the effective primary stress intensity, are derived from the values of Max(P_m), Max($P_L + P_b$) and ΔQ (respectively the maximum value of the primary membrane stress intensity, the maximum value of the stress intensity of the sum of the primary stresses and the maximum value of the secondary stress range), without taking into account the overstress but corrected respectively by an additional term which depends on the primary stress due to overload [5]. Table 3 shows the results on the most critical path (path2). For comparison, both results for the “efficiency index” rules and the alternative “$3S_m$” rules are reported. Furthermore for each result the percentage margin compared to the limit have been indicated. Those configurations that don’t satisfy the P-damage verification are strikethrough.

It should be noted that RCC MRx [5] code does not provide a quantitative evaluation of a “short duration” load, nor a clear definition explaining when a load can be considered of “short duration” or not.

The authors assumed the TFCFD as an overload of short duration, since the time of a Toroidal field coil fast discharge could be considered not comparable with respect to a normal operation plasma pulse time (assumed 2 h [12]). However, since clarifications on these issues are needed, the authors considered useful the verification of the RB3261.1112 rules, assuming the TFCFD pressure applied simultaneously with the coolant pressure, instead as an overload of short duration. In addition, since RCC-MRx codes provides also an alternative

Table 2
P Damage elastic analysis verification path1 – stress values with gray background exceed the stress criteria.

Input parameters of FEM model							Type P Damage Elastic Analysis **RB 3251.112 path1**	
Configurations	**T_{os}**	**T_{is}**	**P_{TFCD}**	**PTFCD constant**	**$H_{base\_constant}$**	**Coolant Pressure**	**Pm ≤ Sm = 130Mpa @200°C**	**Pl+Pb ≤ 1.5Sm = 195Mpa @200°C**
Units	**m**	**m**	**Pa**	**MPa·m**	**W/cm³**	**MPa**	**MPa**	**MPa**
DP 1					8.50E+05		**80**	**218**
DP 2					9.50E+05	3.15	**80**	**218**
DP 3			9.00E+05	0.054	1.05E+06		**80**	**218**
DP 4					8.50E+05		**72**	**127**
DP 5					9.50E+05	1	**72**	**127**
DP 6					1.05E+06		**72**	**127**
DP 7			1.40E+06	0.084		3.15	**118**	**265**
DP 8		0.06	1.90E+06	0.114	8.50E+05		**155**	**312**
DP 9	0.06		1.40E+06	0.084		1	**110**	**174**
DP 10			1.90E+06	0.114			**148**	**222**
DP 11			9.00E+05	0.054			**80**	**218**
DP 12			1.40E+06	0.084		3.15	**118**	**265**
DP 13			1.90E+06	0.114	4.00E+05		**155**	**312**
DP 14			9.00E+05	0.054			**72**	**127**
DP 15			1.40E+06	0.084		1	**110**	**174**
DP 16			1.90E+06	0.114			**148**	**222**
DP 17		0.08	6.75E+05				**58**	**192**
DP 18	0.08	0.08					**65**	**126**
DP 19	0.075	0.085	6.35E+05				**47**	**139**
DP 20	0.07			0.054	8.50E+05	3.15	**46**	**150**
DP 21	0.075	0.09	6.00E+05				**45**	**135**
DP 22	0.06						**47**	**174**
DP 23	0.065						**48**	**168**

Table 3
S Type damage on the critical "path2″ – stress values with gray background exceed the stress criteria.

Input parameters of FEM model							S TYPE DAMAGE path2					
Configurations	**T_{os}**	**T_{is}**	**P_{TFCD}**	**PTFCD constant**	**$H_{base\_constant}$**	**Coolant Pressure**	**RB3261.1118 3Sm =390MPa @200°C**		**RB 3261.1116 P1≤1.3Sm=169MPa @200°C**		**RB 3261.1116 P2≤1.3x1.5Sm=254MPa @200°C**	
Units	**m**	**m**	**Pa**	**MPa·m**	**W/cm³**	**MPa**	**MPa**		**MPa**		**Mpa**	
DP 1			9.00E+05	0.054	8.50E+05	3.15	**384**	2%	**246**	**-46%**	**155**	**39%**
DP 2			9.00E+05	0.054	9.50E+05	3.15	**406**	-4%	**253**	**-50%**	**158**	**38%**
DP 3			9.00E+05	0.054	1.05E+06	3.15	**429**	-10%	**260**	**-54%**	**161**	**37%**
DP 4			9.00E+05	0.054	8.50E+05	1	**302**	23%	**240**	**-42%**	**194**	**24%**
DP 5			9.00E+05	0.054	9.50E+05	1	**324**	17%	**246**	**-46%**	**179**	**29%**
DP 6	0.06	0.06	9.00E+05	0.054	1.05E+06	1	**347**	11%	**253**	**-50%**	**168**	**34%**
~~DP 7~~			~~1.40E+06~~	~~0.084~~	~~8.50E+05~~	~~3.15~~	**~~424~~**	~~-9%~~	**~~344~~**	**~~-104%~~**	**~~181~~**	**~~29%~~**
~~DP 8~~			~~1.90E+06~~	~~0.114~~	~~8.50E+05~~	~~3.15~~	**~~464~~**	~~-19%~~	**~~443~~**	**~~-162%~~**	**~~207~~**	**~~19%~~**
DP 9			1.40E+06	0.084	8.50E+05	1	**343**	12%	**338**	**-100%**	**261**	**-3%**
DP 10			1.90E+06	0.114	8.50E+05	1	**384**	2%	**436**	**-158%**	**327**	**-29%**
DP 11			9.00E+05	0.054	4.00E+05	3.15	**283**	28%	**215**	**-27%**	**152**	**40%**
~~DP 12~~			~~1.40E+06~~	~~0.084~~	~~4.00E+05~~	~~3.15~~	**~~323~~**	~~17%~~	**~~313~~**	**~~-85%~~**	**~~192~~**	**~~24%~~**
~~DP 13~~			~~1.90E+06~~	~~0.114~~	~~4.00E+05~~	~~3.15~~	**~~363~~**	~~7%~~	**~~412~~**	**~~-144%~~**	**~~232~~**	**~~9%~~**
DP 14			9.00E+05	0.054	4.00E+05	1	**201**	48%	**208**	**-23%**	**257**	**-1%**
DP 15			1.40E+06	0.084	4.00E+05	1	**242**	38%	**307**	**-81%**	**376**	**-48%**
DP 16			1.90E+06	0.114	4.00E+05	1	**283**	27%	**405**	**-140%**	**495**	**-95%**
DP 17		0.08	6.75E+05				**324**	17%	**191**	**-13%**	**127**	**50%**
DP 18	0.08	0.08	6.75E+05				**350**	10%	**182**	**-8%**	**123**	**52%**
DP 19	0.075	0.085	6.35E+05				**339**	13%	**174**	**-3%**	**116**	**54%**
DP 20	0.07			0.054	8.50E+05	3.15	**325**	17%	**168**	**0%**	**111**	**56%**
DP 21	0.075	0.09	6.00E+05				**328**	16%	**168**	**0%**	**113**	**56%**
DP 22	0.06						**309**	21%	**170**	**-1%**	**115**	**55%**
DP 23	0.065						**317**	19%	**169**	**0%**	**114**	**55%**

rule RB3261.1118 based on the "3Sm" criterion, our assessment took into account also this rule (Table 3).

5. Conclusion

The aim of the present assessment consisted on the check of the structural integrity of DEMO Vacuum Vessel inboard wall studying and summarizing all provided rules in the relevant vessel design code (RCC MRx). The last version of the RCC MRx (i.e. RB 3261.1113) does not quantify the load duration that allows the consideration as *"overload of short duration"*. The TFCFD pressure, whose peak lasts about 5 s before it decreases exponentially within about 1 min, was assumed by the as an overload of short duration. This assumption is not validated hence all results are tentative. Further discussions, also with technicians of Normative Authority (i.e. AFCEN) are needed in order to clarify this matter.

With the aforementioned assumption the structural integrity of the inboard wall is verified in the configurations DP20, DP21, DPA23 (Table 2 and Table 3). In other words the thickness of the inner shell of the VV inboard wall (in both configuration sets) shall be increased at least in the areas adjacent to the path 1 and path2 (Fig. 7) using T-shape adaptors [13]. It is clear that a more detailed analysis on a design with implemented T-shape adaptors is needed as such as the definition of variation of TFCFD radial pressure along the inner shell in the case of a variable thickness.

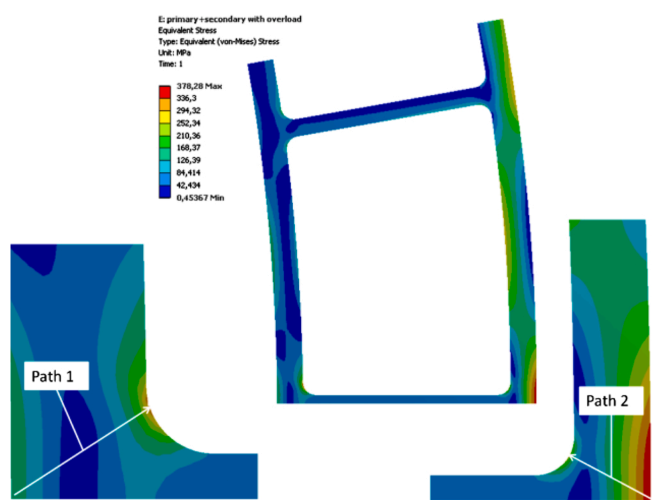

Fig. 7. Paths for stress linearization.

CRediT authorship contribution statement

Rocco Mozzillo: Writing - original draft, Writing - review & editing, Project administration, Investigation, Formal analysis. **Christian Bachmann:** Conceptualization, Funding acquisition. **Giacomo Aiello:** Investigation, Conceptualization. **Domenico Marzullo:** Methodology, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

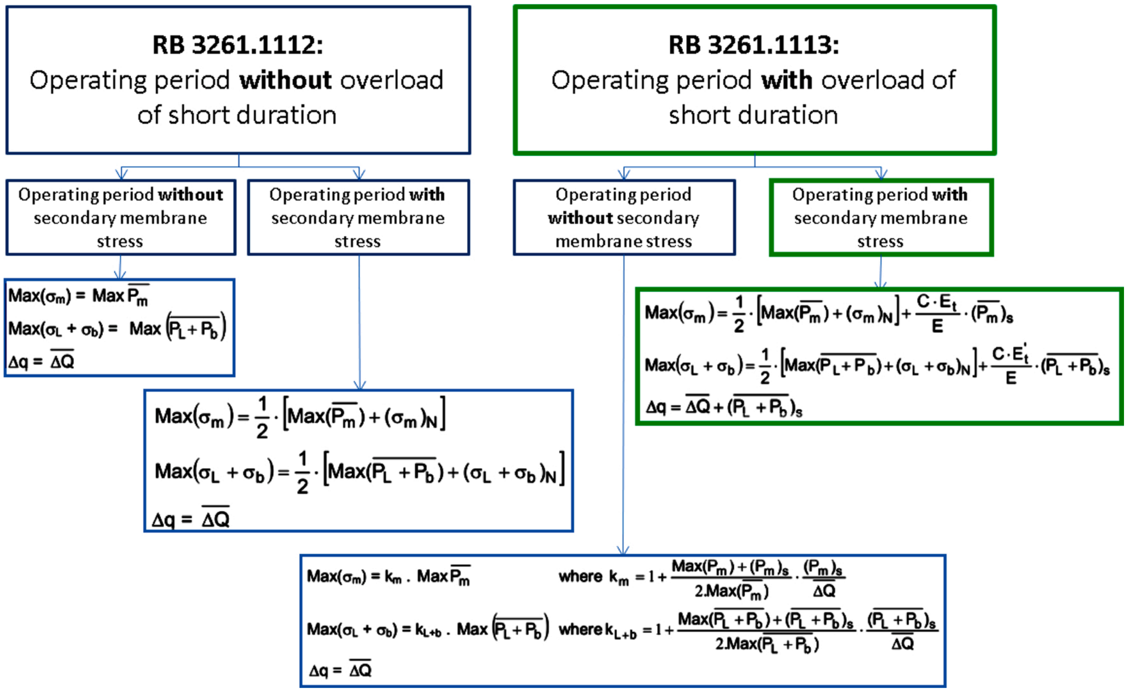

Fig. 8. RB 3260: Rules for prevention of S Type Damage – Elastic analysis [5].

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