Preliminary structural assessment of DEMO vacuum vessel against a vertical displacement event

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HIGHLIGHTS

- The paper focuses on a preliminary structural analysis of the current concept design of DEMO vacuum vessel.
- The Vacuum Vessel was checked against the VDE in combinations with the weight force of all components that the vessel shall bear.
- Different configurations for the vacuum vessel supports are considered, showing that the best solution is VV supported at the lower port.
- The analyses evaluated the "P damage" according to RCC-MRx code.

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ABSTRACT

This paper focuses on a preliminary structural analysis of the current concept design of DEMO vacuum vessel (VV). The VV structure is checked against a vertical load due to a Vertical Displacement Event in combination with the weight force of all components that the main vessel shall bear. Different configurations for the supports are considered. Results show that the greatest safety margins are reached when the tokamak is supported through the lower ports rather than the equatorial ports, though all analyzed configurations are compliant with RCC-MRx design rules.

1. Introduction

Disruptions may be unavoidable events for future fusion reactors and thus they are a source of major concern for future tokamak devices [1]. Disruptions can indeed cause vertical displacement events (VDE) which are uncontrolled vertical motion of the plasma column in tokamaks that brings it in contact with the surrounding structures. For this, the expected vertical load due to a VDE becomes the very first design load to consider when designing the vacuum vessel of a tokamak.

The aim of the present paper is indeed to provide a first structural assessment against a VDE of the vacuum vessel (VV) of the demonstration power plant (DEMO), which has to be operational by 2050 [3,4].

It is understood that other kinds of loads (e.g. seismic loads) could be considered as well, but as a first step in dimensioning the vessel structure, just the VDE is taken into account here.

Generally, to prove the structural integrity of the VV according to RCC-MRx code [10], three different types of damages should be evaluated:

- P type damage[1]
- S type damage[2]
- Buckling[3] (with manufacturing imperfection)

In this work we limited our analysis just to "type P" damage. A VDE is indeed an event of Category 3 and the Level C criteria must be applied [5]. According to RCC-MRx - RB 3253 fatigue analyses

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[1] According to RCC- MRx: RB 3121, RB 3250.
[2] According to RCC- MRx: RB 3122, RB 3260.
[3] According to RCC- MRx: RB3123, RB 3270.

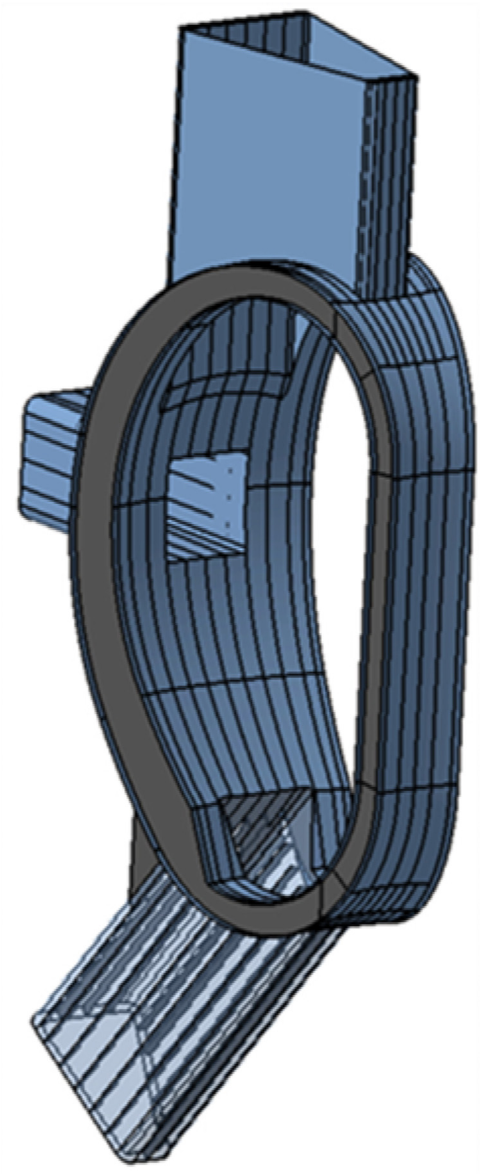

Fig. 1. 3D model of DEMO VV as conceived in [2].

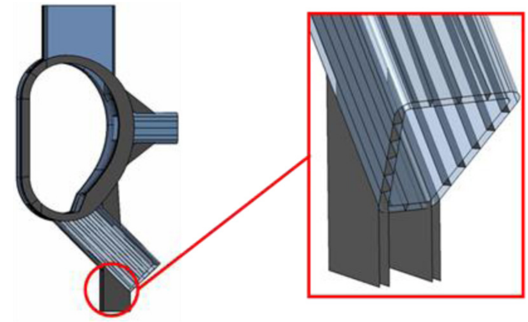

Fig. 2. Supports on the lower port joined to the four port sidewall.

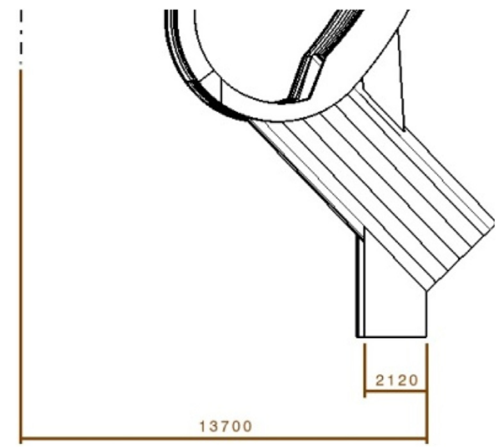

Fig. 3. L1 Supports configuration.

are not required, while the buckling phenomena will be studied in more advanced design stages.

At time of writing the concept design of DEMO VV (2014) is characterized by a double-wall structure with shell and ribs (see Fig. 1) [2]. The ports are joined to the main vessel structure through proper gusset plates. The structural assessment is based on finite element method (FEM) that is being discussed in the next sections. In particular, according to RCC-MRx - RB 3242 "*Elastoplastic analysis of a structure subjected to a monotonic loading*", the VV has to be verified against the maximum vertical load due to a VDE, as well as its own weight. Therefore the weight of all the components that are not modelled must be considered as well in the calculation. Moreover, given the materials and the design loads, the behaviour of a structure strongly depends on how it is supported. Thus, different possible configurations for the supports of the vacuum vessel are being preliminarily discussed in the next section.

2. Supports configurations

The VV is a double-wall welded structure; its supports were simplified in this assessment as supporting plates joined to the ports sidewalls. This results in four separate plates for each support (Fig. 2).

These support plates were considered "infinitely stiff", since they are not the subject of the present analysis.

The VV could be supported just through the lower port, or through the equatorial port. Moreover, the distance between the actual support and the center of mass of the VV affects the results as well. For this, five possible configurations of the supports have been studied, as stated below:

- **L1 configuration**: The supports are placed as far as possible from the VV (Fig. 3), given the length of the lower port. The distance between the supports and TOKAMAK axis results in about 13700 mm; support plates were chosen to be 2120 mm long. This configuration causes greater values for the bending moment on the lower port.
- **L2 configuration**: The supports are placed at the middle distance between the two extremities of the lower port. The distance between the supports and TOKAMAK axis results in about 12640 mm (Fig. 4).
- **L3 configuration**: The supports of lower port are placed as close as possible to the main chamber. In this configuration, the distance between the supports and TOKAMAK axis is about 11580 mm (Fig. 5).
- **E1 and E2 configurations**: The supports are placed on the equatorial port.

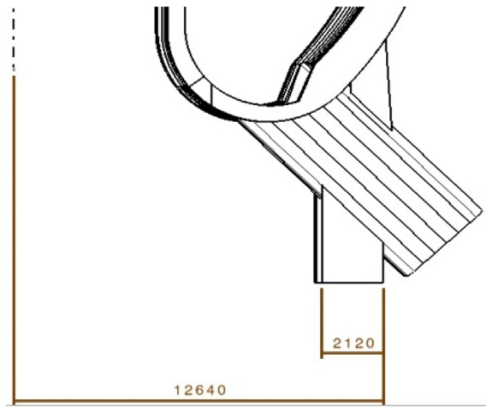

Fig. 4. L2 supports configuration.

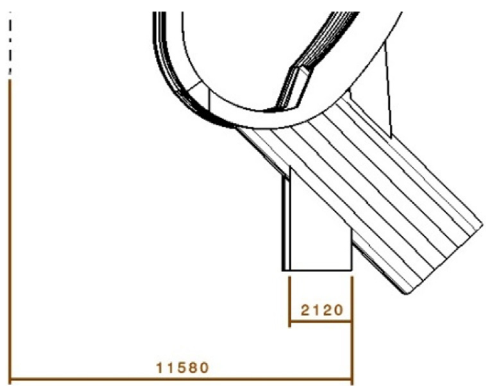

Fig. 5. L3 supports configuration.

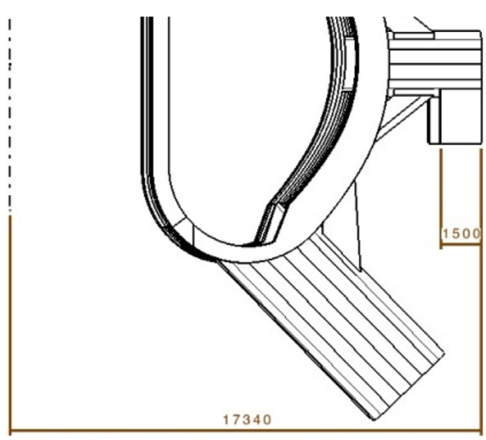

Fig. 6. E1 Supports configuration.

The distance between the supports and TOKAMAK axis is about 17340 mm for E1 configuration and 15845 mm for E2 configuration, corresponding to the minimum and maximum distance from the center of mass of the TOKAMAK respectively. Their length is 1500 mm (Fig. 6).

In conclusion, five different configurations for the supports of the tokamak will be analyzed. The radial distance of the supports from central axis of the tokamak is summarized in Table 1.

3. Finite elements model

As mentioned, the reference design for DEMO VV is a CATIA V5 CAD model of a single sector 22.5° wide that has been discussed in

Table 1
Radial distance of the restraints for the different supports.

Supports configuration	Radial coordinate [mm]
L1	13700
L2	12640
L3	11580
E1	17340
E2	15845

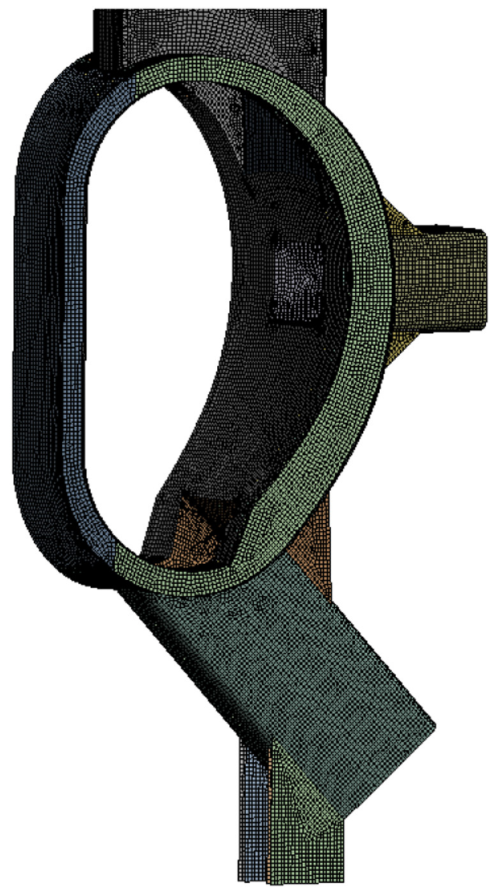

Fig. 7. 3D mesh of DEMO VV.

[2]. FEM analysis was conducted with ANSYS Workbench Release 14.0.

The reference element type for the FE model is **SHELL 181**. The resulting mesh has 91982 nodes and 96015 elements (Fig. 7).

In the following sections the characteristics of the FEM model (i.e. loads, materials and boundary conditions) are being examined in more details.

3.1. Design loads

As mentioned, according to RCC-MRx - RB3242, the structure of the main vessel has to be tested against a vertical displacement event (VDE), as well as its own weight. More precisely, the load combination considered refers to a Category 3 event (Category 3 - Class C: Dead weight + VDEIII) [6].

The worst case occurs during a VDE slow-down 1 [5], when the plasma exerts an overall load of 146 MN along the z axis of the tokamak. On first approximation, the net vertical load for each of the sixteen sectors of the vacuum vessel can be calculated just as:

$$F_z = \frac{F_{VDE}}{N} = \frac{146}{16} = 9.12 \quad [MN] \tag{1}$$

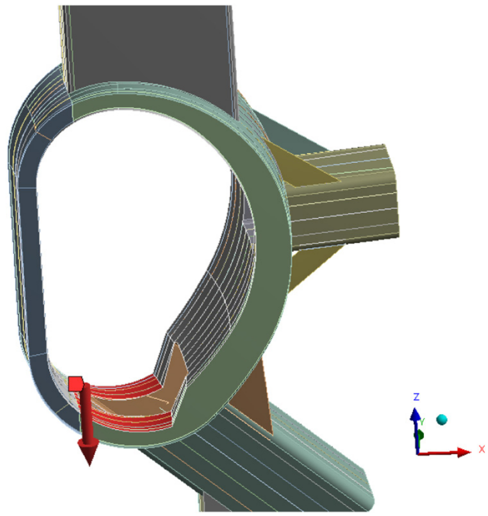

Fig. 8. Load due to VDE.

Table 2
Materials properties at 100 °C.

Material	E [Pa]	ν	Density [kg/m^{-3}]	Behaviour
Custom Stainless steel	1,93 × 10^{11}	0.3	24851[a]	Elasto - plastic
Elastic Stainless Steel	1,93 × 10^{11}	0.3	7850	Linear Elastic
High stiffness Steel	1 × 10^{16} [a]	0.3	7850	Linear Elastic

[a] Artificial values.

The vertical load has been applied to the surface highlighted in Fig. 8. Its direction is parallel to the z axis and its verse is negative with respect to the cylindrical coordinate system.

With reference to the weight force, the estimated total mass for a DEMO sector [5], including port extensions, ducts, plugs, in-wall shielding, blanket modules, divertor modules is:

$$M = 1.15 \cdot 10^6 \quad [\text{kg}] \tag{2}$$

However, since these components have not been modeled yet with the degree of accuracy needed for a significant FEM analysis, the density value of VV material has been chosen to take into account the actual weight force that the vessel has to bear (see Section 3.2). Anyway, this "trick" does not affect the results, since dynamic aspects are not considered in the present study. Moreover, it is worth noticing that, in this way, the weight force is uniformly distributed through the whole VV structure, but this approximation is acceptable for the purposes of the present study.

3.2. Materials

The reference material for the VV is the AISI 316L(N) stainless steel. However, three different material types have been defined in the FE model (see Table 2). The properties of the materials refer to the operating temperature of the vacuum vessel (100° C).

- **Custom stainless steel** was applied to the main structure of the main vessel and ports. As mentioned, an artificial density value of 24,851 kg/m^{-3} has been assigned to this material to account for the masses of all the components that lay on the main vessel, yet not modelled, such as port extensions, plugs, in-wall shielding, blanket modules, divertor modules, etc. [5]. The material behaviour is elastoplastic. The minimum true stress-strain curve used for calculations is summarized in Table 3.
- **Elastic Stainless Steel** is an ideal linear elastic material that was applied, in some cases, just to the gusset plates in order to avoid their premature collapse due to plastic deformations and thus to investigate the safety margin of the main vessel structure. This aspect will be better illustrated in the next sections.
- **High stiffness steel** is a custom material with an artificial modulus of elasticity that is five orders of magnitude greater than the real stainless steel. This means that it be considered as "infinitely stiff" with respect to the other material used for FEM modelling. This material was applied to the support plates of the VV to avoid their possible failure and to reduce singularity effects due to the restraints set up on them. This simplification is acceptable because the present study does not investigate supports structure.

Table 3
Stress-strain relationship corresponding to minimum true stress-strain curve for AISI 316 L(N) stainless steel [6].

Operating temperature = 100 °C	
Plastic Strain	Stress [MPa]
2.69 × 10^{-4}	50
5.54 × 10^{-4}	100
7.88 × 10^{-4}	125
10.69 × 10^{-4}	140
13.92 × 10^{-4}	150
18.99 × 10^{-4}	160
26.94 × 10^{-4}	170
39.26 × 10^{-4}	181
58.01 × 10^{-4}	191
86.05 × 10^{-4}	202
127.23 × 10^{-4}	213
3910.28 × 10^{-4}	677

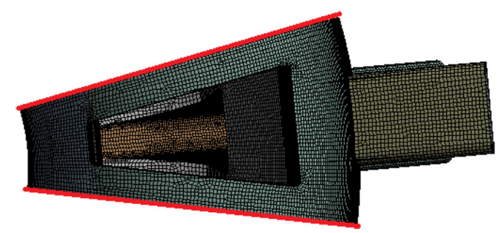

Fig. 9. Symmetry boundary conditions on the left and right edges of VV single sector.

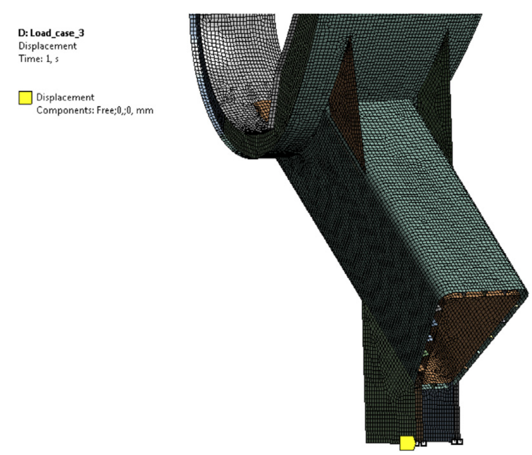

Fig. 10. Position of the restraints on the support plates.

3.3. Boundary conditions

A planar symmetry condition has been placed on the two boundary edges of the VV sector (at −11.25° and +11.25°, respectively) (see Fig. 9).

To allow rigid rotations the restraints have been placed just on one node of each support plate (Fig. 10).

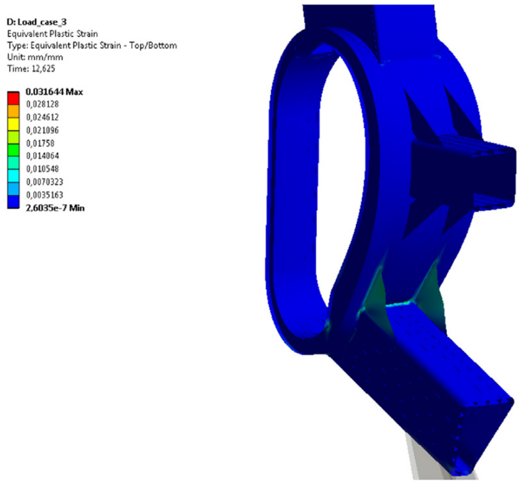

Fig. 11. Equivalent Plastic Strain, Configuration EP1, Last Load multiplication factor 2.53.

As mentioned, we have supposed five different configurations for tokamak supports. The vessel support was constrained against rotation around the vertical axis and against translation along a direction inclined with respect to the vertical axis. A radial constraint cannot be implemented as it would constrain the thermal expansion of the VV.

4. Results

In all configurations the main vessel has elastoplastic behaviour, while the material of the gusset plates can be linear elastic or elastoplastic. Since the load is increased in multiple load steps, the calculation diverges due to excessive plastic deformations (hereinafter referred to as "plastic instability"). The last load before the loss of convergence of the Newton-Raphson algorithm [7] is assumed as the actual *collapse load*. It should be emphasized that this is a conservative assumption, since the correspondent *maximum equivalent strain* (see Table 4) is always less than 10% [8]. Moreover some analyses conducted on ITER Vacuum Vessel [9], under similar load and boundary conditions, confirmed that using shell models is conservative in terms of global displacements with respect to the equivalent solid model. The *collapse load factor* is thus easily calculated as the ratio between collapse and design load. The main outcome of the assessed configurations is summarized in Tables 4 and 5.

As one can see, in all configurations the load factor is higher than 2.0, as required by RCC-MRx-2012 code – RB 3251.12.

As aforementioned, in some cases a linear elastic behaviour was assigned to the gusset plates, while the VV was still elastoplastic. This allows estimating how much load the main vessel alone can withstand if the gusset plates were "infinitely strong".

However, in the following subsections just the "realistic" cases (namely, the configurations with elastoplastic behaviour for gusset plates) are being discussed in more detail.

The consistency of the FEM model has been checked by comparing the resulting reaction forces to the expected values for each configuration.

4.1. Configuration EP1

The resulting load factor (2.53) is far lower than the other combination for L1 configuration of supports.

As shown in Fig. 11, the collapse happens at the lower port gusset plates that are affected by a plastic instability phenomenon.

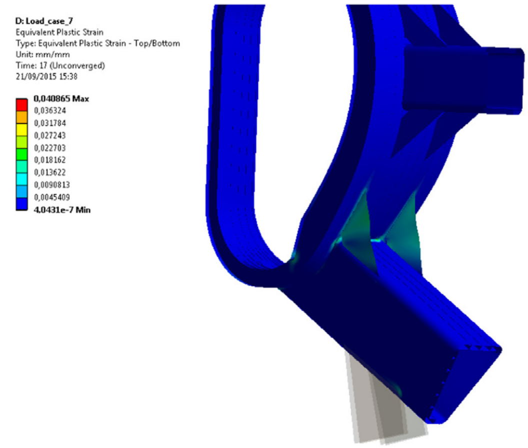

Fig. 12. Equivalent Plastic Strain for configuration EP2.

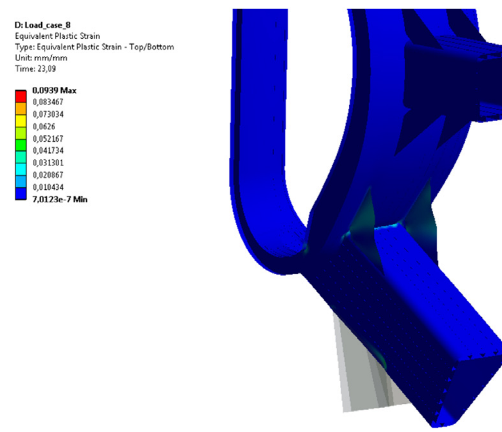

Fig. 13. Equivalent Plastic Strain for configuration EP4.

4.2. Configuration EP3

This case is very similar to configuration EP1, except for the position of the restraints with respect to the tokamak central axis. The load factor (3.29) is better than the other combination. Also in this case the gusset plates of the lower ports are affected by a plastic instability phenomenon (see Fig. 12).

4.3. Configuration EP4

This case is comparable to cases EP3 and EP1 since boundary conditions and the behaviour of gusset plates are virtually identical. However, as expected, the limit load for this combination is greater than the others, because the support is closer to the central axis of the tokamak and thus the bending moments are lower.

As shown in Fig. 13, also in this case, the gusset plates of the lower ports collapse due to plastic instability.

4.4. Configuration EP6

In this case, gusset plates have an elastoplastic behaviour and the equatorial ports are free to move in radial direction. The VV collapses both due to instability of both upper gusset plates and port sidewalls of equatorial ports (Fig. 14). The resulting load factor for this configuration is 2.88. As one can see, the strain is always less than 10%. Indeed, higher values are due to local effects at the interface between port and supports (modelled as infinitely stiff) and thus can be overlooked.

Table 4
Results in brief: "realistic" cases (elastoplastic behaviour for gusset plates).

Configuration	Support type	Load factor	Max Equivalent Plastic Strain	Comments
EP1	L1	2.53	3.2%	Realistic case for L1 supports. Collapse due to plastic instability of gusset plates.
EP3	L2	3.29	4.0%	Realistic case for L2 supports. Collapse due to plastic instability of the gusset plates.
EP4	L3	4.62	9.4%	Realistic case for L3 supports. Collapse due to plastic instability of the gusset plates. Best combination for lower supports.
EP6	E1	2.88	8,7%	Realistic case for E1 supports configuration
EP8	E2	4.24	8,7%	Realistic case for E2 supports configuration

Table 5
Results in brief: Linear elastic behaviour for gusset plates.

Configuration	Support type	Load factor	Comments
LE2	L1	7.98	High plastic strain; This configuration allows estimating how much load the main vessel can withstand (gusset plates excluded).
LE5	E1	2.66	Central port sidewalls collapse; This configuration allows estimating how much load the main vessel can withstand (gusset plates excluded).
LE7	E2	4.55	Plastic instability phenomenon occurs on the sidewalls of the central port. This configuration allows estimating how much load the main vessel can withstand (gusset plates excluded). Best combination for equatorial supports

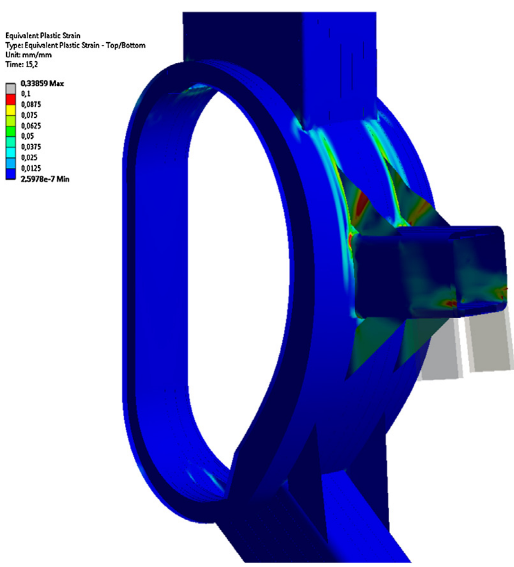

Fig. 14. Equivalent Plastic Strain for configuration EP6.

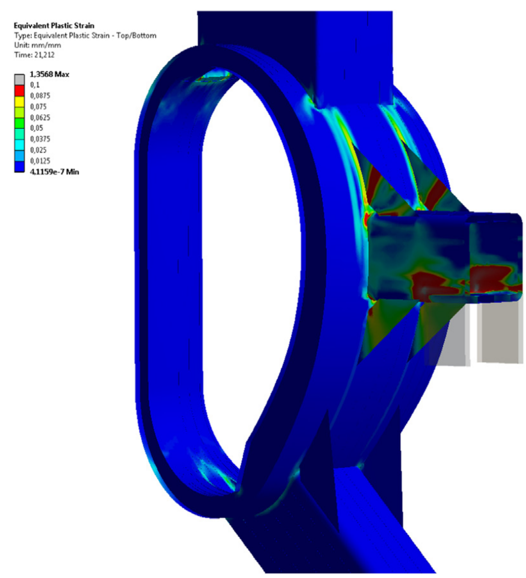

Fig. 15. Equivalent Plastic Strain for configuration EP 8.

4.5. Configuration EP8

This case is similar to the previous one in terms of boundary conditions and behaviour of gusset plates. However, the radial coordinate of restraints is reduced and, consequently, the bending moment is expected to be lower than the one of the latter case.

Again, the collapse occurs both in the gusset plates and in the sidewalls of the equatorial ports, but this time the load factor is higher (4.24). As for configuration EP6, the maximum plastic strain greater than 10% is likely caused by stress concentration due to joint between materials type with different behaviours (Fig. 15).

5. Conclusion and future works

A FEM-based structural analysis has been conducted on the current design of DEMO VV [2]. The choice of using a FE shell model is acceptable and also provides conservative results since the maximum plastic deformation at collapse is quite limited. Eight configurations (corresponding to different possible combinations of supports and material behaviours) were considered. The VV structure was checked against a load due to a Vertical Displacement Event in combination with the weight force of all components that the main vessel shall bear; no other types of load were addressed. The results of FEM analysis showed that the structure of the main vessel is sufficient to withstand the most severe vertical loads (VDE and dead weight). In general, the most stressed components are the gusset plates that join ports to the main vessel structure; their collapse can be attributed to an elastoplastic instability phenomenon (though not specifically modelled). Further investigations will be conducted in more detailed design phases. As shown in Fig. 16, the collapse load factor increases with the decrease of the radial position of the restraints, due to lower bending moments.The results for "realistic" configurations are summarized in Table 6. As expected, L3 is the most promising configuration for DEMO supports. Anyway, also in the other configurations the load factor is higher than 2.0,

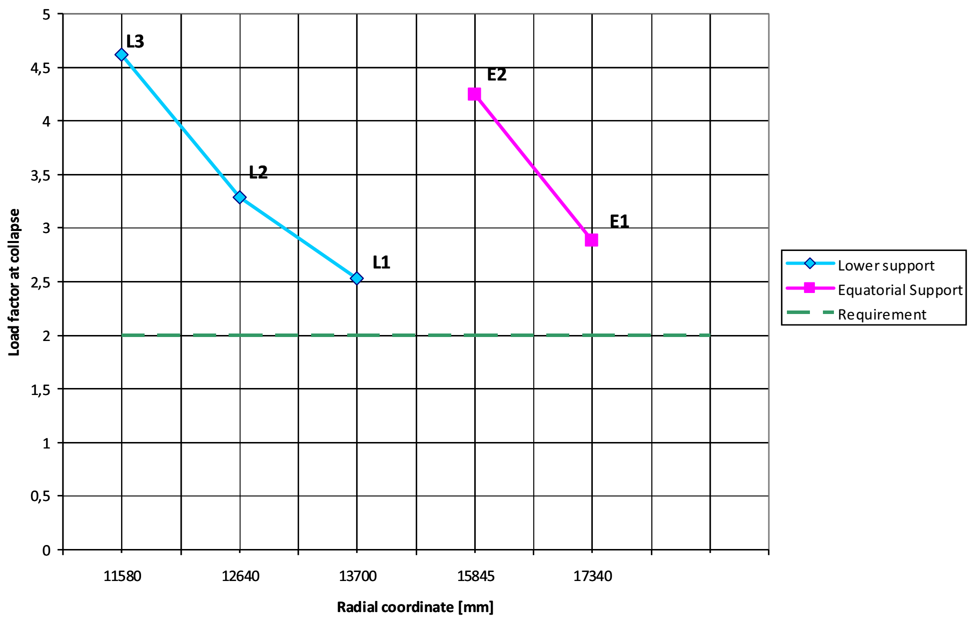

Fig. 16. Collapse load factors for different supports configurations (elastoplastic behaviour for gusset plates).

Table 6
Results for "realistic" configurations.

Supports configuration	Constraint Radial Coord. [m]	Collapse load factor
L1	13.7	2.53
L2	12.6	3.29
*L*3	11.6	4.62
E1	17.3	2.88
E2	15.8	4.24

as required by RCC-MRx-2012 code – RB3251.12 to prevent type-P damages due to plastic instability [10], therefore both the equatorial ports and the lower ports would be capable to support the VV. It is worth noticing that the design criteria used in the present analysis are Level C criteria.

The inclination of the lower port is very beneficial for the load-bearing capability of the VV. Since, also with reference to the integration with the magnet supports, the lower port seems to be the most suitable candidate to support the vessel, the design and inclination of the lower port should be a focus of future work.

Acknowledgements

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