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Structural assessment of the DEMO Vacuum Vessel concept design

Rocco Mozzillo (a), Andrea Tarallo (a), Domenico Marzullo (a), Christian Bachmann (b), Giuseppe Di Gironimo (a), Giuseppe Mazzone (c)

[a] *CREATE, University of Naples Federico II, DII, P.le Tecchio 80, 80125, Naples, Italy*
[b] *EUROfusion PMU, Boltzmannstraße 2, 85748 Garching, Germany*
[c] *Unità Tecnica Fusione - ENEA C.R. Frascati, Via E. Fermi 45, 00044 Frascati, Italy*

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.

Keywords: DEMO Vacuum Vessel, Finite Element Method (FEM), Elasto-plastic analysis.

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.

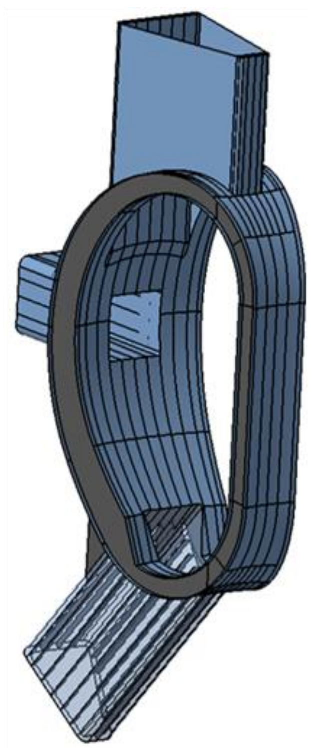

Figure 1 3D model of DEMO VV as conceived in [2]

The aim of the present paper is indeed to provide a first structural assessment of the vacuum vessel (VV) of the demonstration power plant (DEMO), which has to be operational by 2050 [3][4]. The current concept design of DEMO VV (2014) is characterized by a double-wall structure with shell and ribs (see figure 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. However, according to RCC MRx - RB3242 "*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, though not modelled. Moreover, given the materials and the design loads, the behavior of a structure strongly depends on how it is supported. Thus, different possible configurations for the supports of the vacuum vessel are being discussed and analyzed 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 (figure 2).

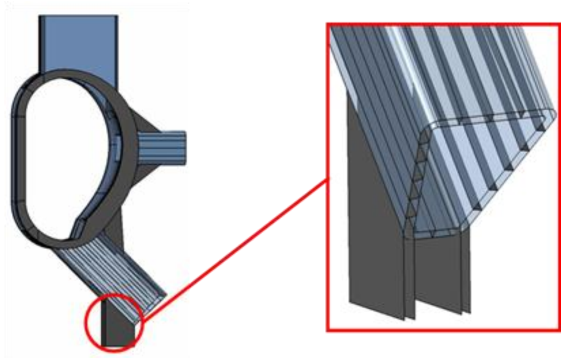

Figure 2 Supports on the lower port joined to the four port sidewall

These support plates were considered infinitely stiff, since they are not the subject of the present analysis.
The VV could be supported 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 far from the VV (figure 3). The distance between the support and TOKAMAK axis results in about 13700mm; support plates were chosen to be 2120mm long. This configuration causes greater values for the bending moment on the lower port.

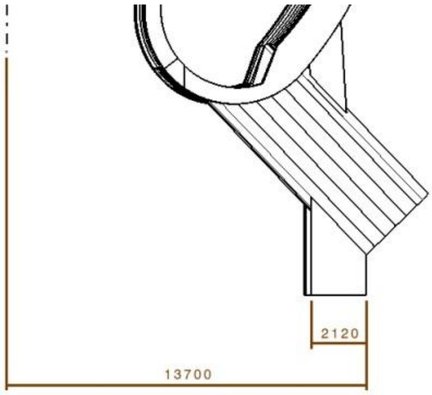

Figure 3 L1 Supports configuration

- **L2 configuration**: the supports are placed at the center of the lower port. The distance between the supports and TOKAMAK axis results in about 12640mm (Figure 4).

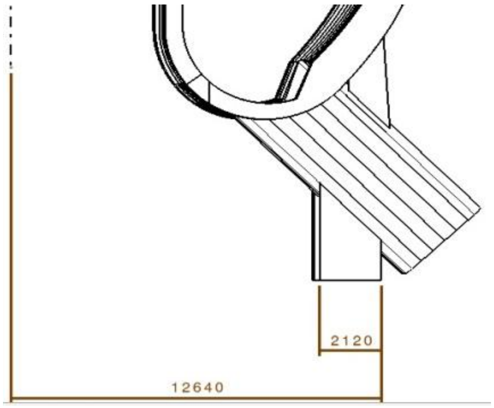

Figure 4 L2 supports configuration

- **L3 configuration**: the supports of lower port are placed close to the main chamber. In this configuration, the distance between the supports and TOKAMAK axis is about 11580mm (Figure 5).

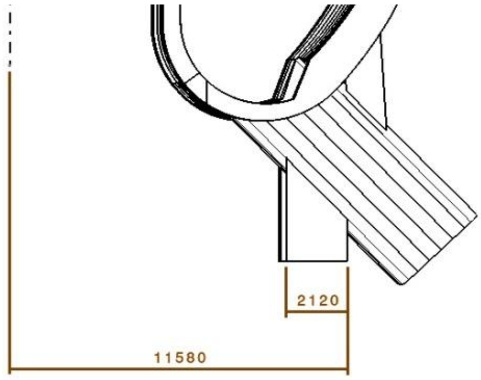

Figure 5 L3 supports configuration

- **E1 and E2 configurations**: the supports are placed on the equatorial port. The distance between the supports and TOKAMAK axis is about 17340mm, and **15845mm** respectively. Their length is 1500mm (Figure 6)

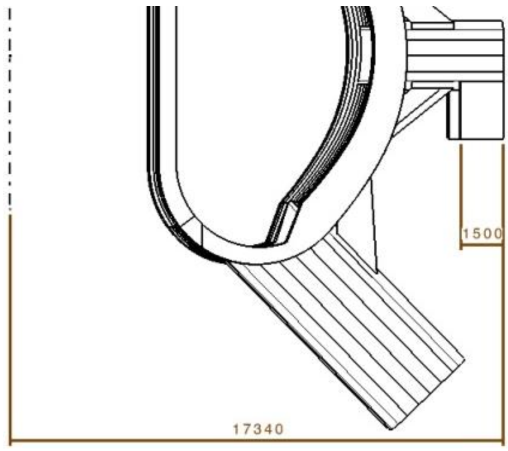

Figure 6 E1 Supports configuration

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.

Table 1 - Restraints positions for the different supports

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

3. Finite elements model

As mentioned, the reference design for DEMO VV is a CATIA V5 CAD model of a single sector 22.5 degree wide that has been discussed in a previous work [2]. FEM analysis was conducted with ANSYS Workbench Release 14.0.

Figure 7 3D mesh of DEMO VV

The reference element type for the FE model is **SHELL 181**. The resulting mesh has 91982 nodes and 96015 elements (figure 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 [6]:

Category 3: Class C: Dead weight + VDEIII

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:

$$F_z = \frac{F_{VDE}}{N} = \frac{146}{16} = 9.12\,[\mathrm{MN}] \qquad (1)$$

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

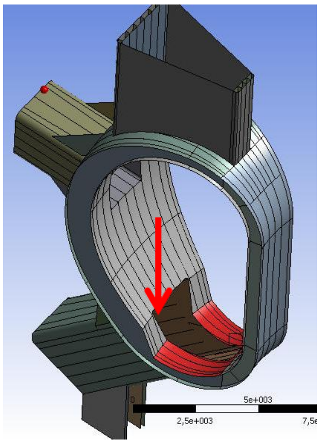

Figure 8 Direction and verse of the load

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:

$$M = 1.15 \cdot 10^3\,[tons] \qquad (16)$$

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 changed to take into account the actual weight force that the vessel has to bear as well (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 316 L(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).

Table 2 Materials properties at 100°C

Material	**E [Pa]**	**ν**	**Density [kg m^{-3}]**	**Behavior**
Custom Stainless steel	$1{,}93 \cdot 10^{11}$	0.3	**24851**	Elasto - plastic
Elastic Stainless Steel	$1{,}93 \cdot 10^{11}$	0.3	7850	Linear Elastic
High stiffness Steel	$\mathbf{1 \cdot 10^{16}}$	0.3	7850	Linear Elastic

- **Custom stainless steel** was applied to the main structure of the main vessel and ports. As mentioned, an artificial density value 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 elasto-plastic. The minimum true stress-strain curve used for calculations is summarized in table 3.

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 [Pa]**
$2.69 \cdot 10^{-4}$	$50 \cdot 10^{+6}$
$5.54 \cdot 10^{-4}$	$100 \cdot 10^{+6}$
$7.88 \cdot 10^{-4}$	$125 \cdot 10^{+6}$
$10.69 \cdot 10^{-4}$	$140 \cdot 10^{+6}$
$13.92 \cdot 10^{-4}$	$150 \cdot 10^{+6}$
$18.99 \cdot 10^{-4}$	$160 \cdot 10^{+6}$
$26.94 \cdot 10^{-4}$	$170 \cdot 10^{+6}$
$39.26 \cdot 10^{-4}$	$181 \cdot 10^{+6}$
$58.01 \cdot 10^{-4}$	$191 \cdot 10^{+6}$
$86.05 \cdot 10^{-4}$	$202 \cdot 10^{+6}$
$127.23 \cdot 10^{-4}$	$213 \cdot 10^{+6}$
$3910.28 \cdot 10^{-4}$	$677 \cdot 10^{+6}$

- **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 a bogus modulus of elasticity that is five orders of magnitude greater than the 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. Actually, this simplification is acceptable because the present study does not investigate supports structure.

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 Figure 9).

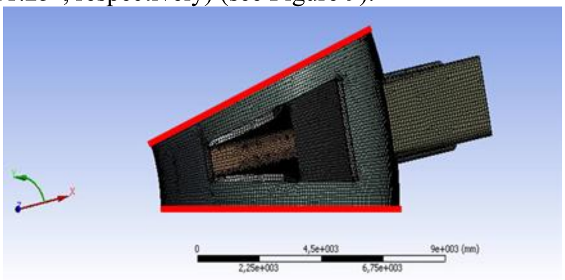

Figure 9 Symmetry boundary conditions on the left and right edges of VV single sector

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

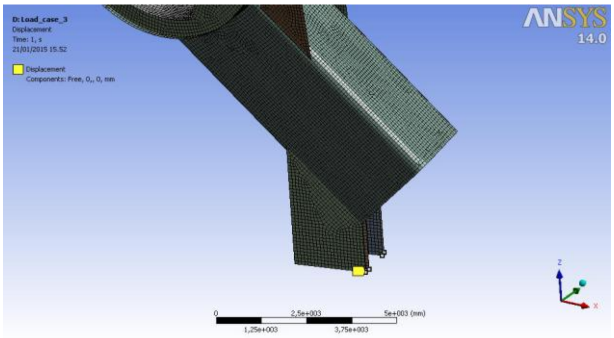

Figure 10 Position of the restraints on the support plates

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

Since in all configurations the material of the main vessel has elasto-plastic behaviour, the load is increased in multiple load steps until the structure collapses due to high plastic deformations. More precisely, each step increases the load magnitude by 20% while the load is applied to the deformed structure. In this way, the *collapse load factor* (i.e. the ratio between the collapse load and the design load) can be easily calculated. The main outcome of the assessed configurations is summarized in Table 4.

Table 4 - Results in brief; "realistic" cases for each support are highlighted.

Config.	**Support type**	**Material behaviour for gusset plates**	**Load factor**	**Comments**
1	**L1**	**Elasto-plastic**	2.53	Realistic case for L1 supports. Collapse due to instability of gusset plates.
2	**L1**	**Linear elastic**	7.98	High plastic strain; This configuration allows estimating how much load the main vessel can withstand (gusset plates excluded).
3	**L2**	**Elasto-plastic**	3.29	Realistic case for L2 supports. Collapse due to instability of the gusset plates.

4	L3	**Elasto-plastic**	**4.62**	Realistic case for L3 supports. Collapse due to instability of the gusset plates. **Best combination for lower supports.**
5	E1	**Linear elastic**	2.66	Central port sidewalls collapse; This configuration allows estimating how much load the main vessel can withstand (gusset plates excluded).
6	E1	**Elasto-plastic**	2.88	Realistic case for E1 supports configuration
7	E2	**Linear elastic**	**4.55**	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**
8	E2	**Elasto-plastic**	4.24	Realistic case for E2 supports configuration

As we can see, in all configurations the load factor is higher than 2.0, as required by RCC-MRx-2012 code - RB3251.12.

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

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

5.1 Configuration nr.1

The resulting load factor (2.53) is far lower than the other combination for L1 configuration. As shown in Figure 11, the collapse happens at the lower port gusset plates that are affected by an instability phenomenon.

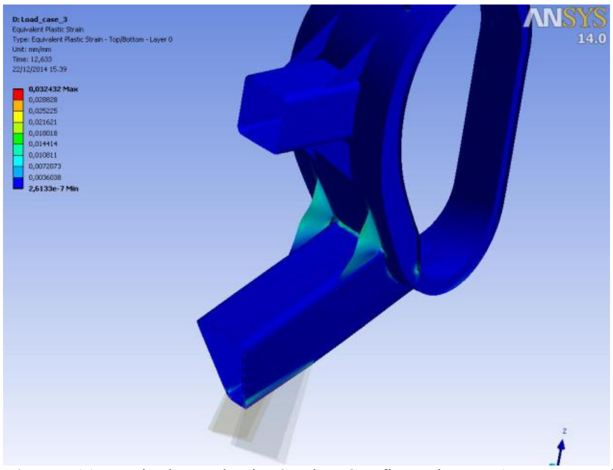

Figure 11 Equivalent Plastic Strain, Configuration nr.1, Last Load multiplication factor 2.53

5.2 Configuration nr.3

This case is very similar to configuration nr.1, 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 an instability phenomenon (see Figure 12).

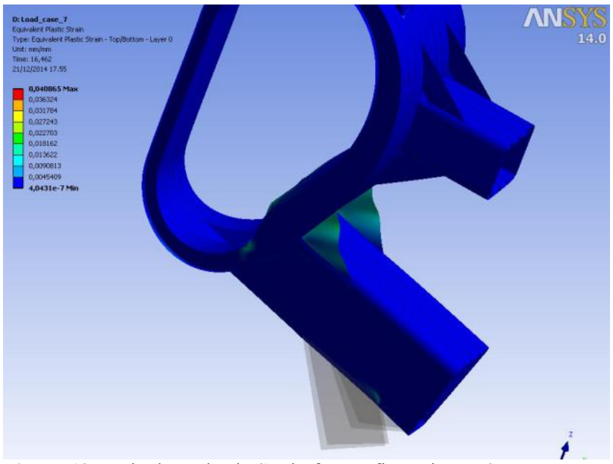

Figure 12 Equivalent Plastic Strain for configuration nr.2

5.3 Configuration nr.4

This case is comparable to cases nr.3 and nr.1 since boundary conditions and the behavior of gusset plates are virtually identical. However, as expected, the limit load for this combination is better 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 Figure 13, also in this case the gusset plates of the lower ports collapse due to structural instability.

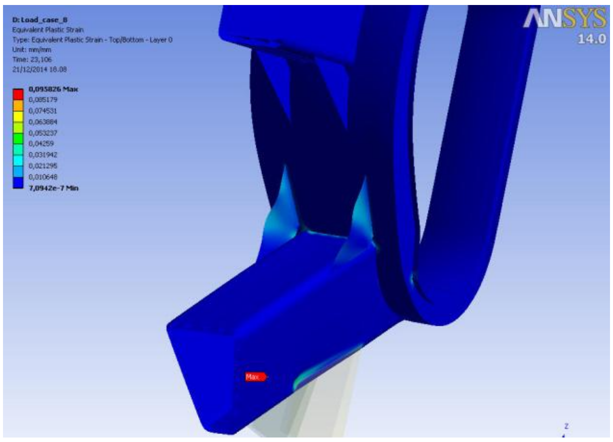

Figure 13 Equivalent Plastic Strain for configuration nr.4

5.4 Configuration nr.6

In this case, gusset plates have an elasto-plastic behavior 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 (Figure 14). The resulting load factor for this configuration is 2.88.

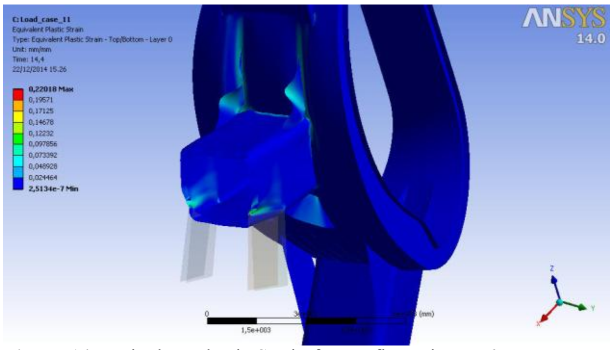

Figure 14 Equivalent Plastic Strain for configuration nr.6

5.5 Configuration nr.8

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

Again, the collapse occurs both on the gusset plates and on the sidewalls of the equatorial ports, but this time the load factor is higher (4.24). However, the maximum plastic strain is higher too. This is likely caused by stress concentration due to joint between materials type with different behaviors (Figure 15).

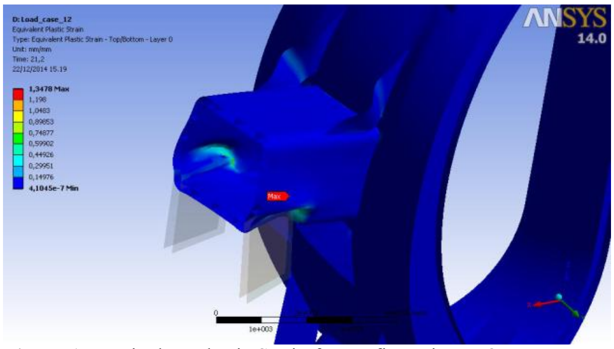

Figure 15 Equivalent Plastic Strain for configuration nr.8

5. Conclusions and future works

A FEM-based structural analysis has been conducted on the current design of DEMO VV [2]. Eight configurations (corresponding to different possible combinations of supports and material behaviours) were considered. The VV structure was 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; 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 elasto-plastic instability phenomenon. Moreover, for each configuration, the corresponding collapse load factor has been calculated. As shown in figure 15, the load factor increases with the decrease of the radial position of the restraints, due to lower bending moments.

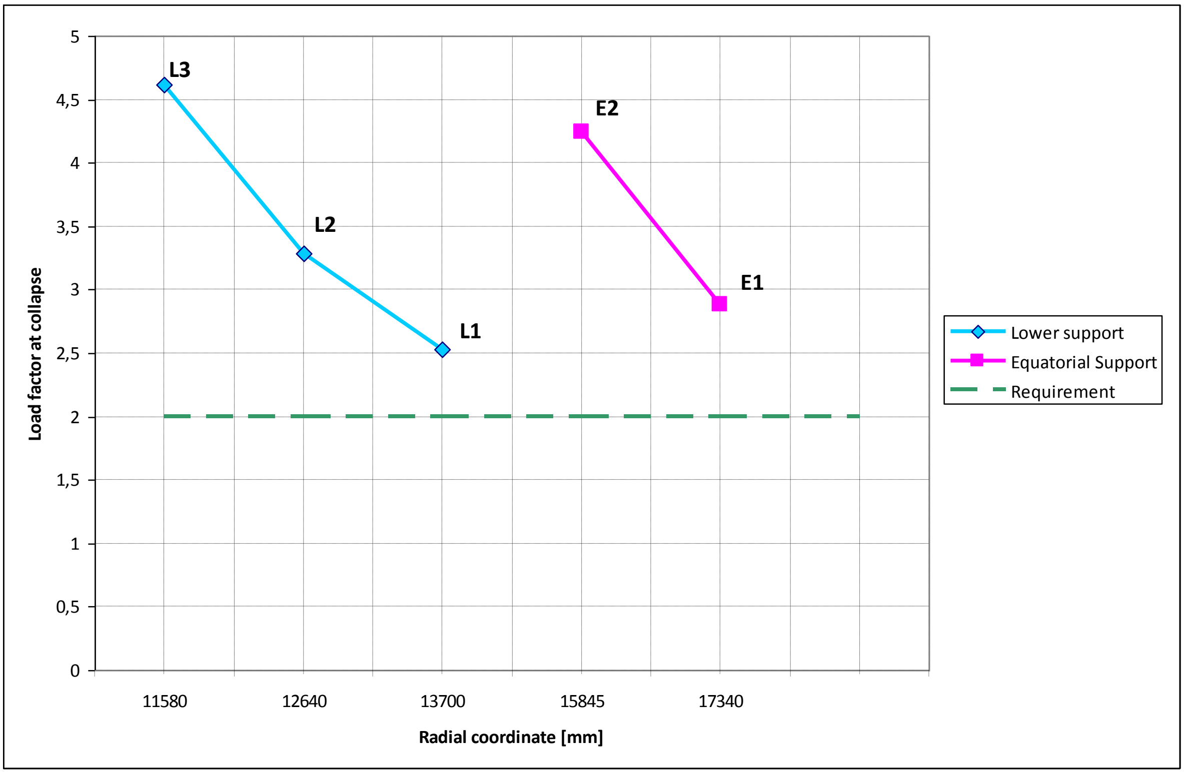

Figure 16 Collapse load factors for different supports configurations (elasto-plastic behaviour for gusset plates)

The results for "realistic" configurations are summarized in Table 5. 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, as required by RCC-MRx-2012 code - RB3251.12 to prevent type-P damages due to plastic instability [7], 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.

Table 5 Results for "realistic" configurations

Support configuration	Constraint Radial Coord. [m]	Collapse load factor
L1	13.7	2.53
L2	12.6	3.29
L3	11.6	4.62
E1	17.3	2.88
E2	15.8	4.24

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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