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This paper describes initial conceptual design studies of the DEMO Vacuum Vessel (VV) carried out within the framework of the EUROfusion Consortium that aims at developing a conceptual design of a DEMO by 2020. Starting from the VV space envelope defined in the DEMO baseline design 2014 the layout of the VV structure was preliminarily defined based on the design criteria provided in RCC-MRx. A surface modeling technique was adopted and efficiently linked to the finite element (FE) code to simplify future FE analyses. In view of possible changes to VV shape and structure during the conceptual design activities a parametric design approach allows incorporating modifications to the model efficiently.

Keywords: DEMO, Conceptual Design, CAD, surface modeling.

1. Introduction

One important objective of the EU fusion roadmap Horizon 2020 is to develop a conceptual design of a *demonstration fusion power reactor* (DEMO) to follow ITER, capable of generating several 100 MW of net electricity to the grid and operating with a closed fuel-cycle by 2050. Most nations involved in the construction of ITER view DEMO as the last step towards the actual exploitation of fusion power [1].

Indeed, with the construction of ITER well underway, attention is now turning to DEMO that should pave the way to future fusion-based commercial reactors. Currently, no conceptual design exists of DEMO and work carried out in the past in Europe on fusion reactor design focused on assessment of safety, environmental and socioeconomic aspects of fusion power [2].

The present work concerns the design of the DEMO Vacuum Vessel (VV). The VV is a toroidal chamber located inside the magnet system aimed at providing an enclosed vacuum environment for plasma. Also, it acts as a first confinement barrier; thus the nuclear pressure vessel design code RCC-MRx is considered in its design. The selected material for VV is AISI 316L(N) stainless steel. The heat transferred to the vessel is actively removed by water circulating in-between the double-shell structure.

The most important components of the VV are the main vessel, the port structures and its supporting system. To withstand the coolant pressure the double-shell steel structure of the DEMO VV is internally reinforced by ribs. Therefore, the first step in the actual structural design of VV was the definition of the shell thickness and the maximum distance between the ribs.

A first 3D model was prepared based on these considerations and used for structural analyses of a full VV sector for the main loads, i.e. dead weight and VDE.

One of the objectives of the present work was to develop light and efficiently to manage CAD and FE models in view of the likely changes in VV structure required during the conceptual design activities on DEMO.

2. Preliminary dimensioning of internal ribs structure for vacuum vessel

As mentioned the VV has a double-wall all-welded box structure with internal stiffeners (*ribs*), as shown in Figure 1.

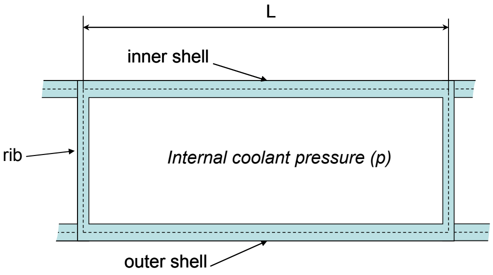

Figure 1 - Shells and ribs structure of VV

The torus shape of VV is divided in 16 separate sectors of 22.5° each (see figure 2).

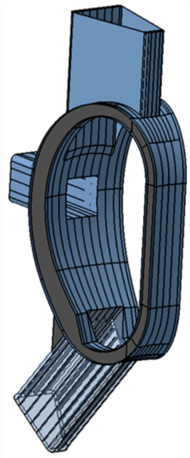

Figure 2 - Box structure of DEMO VV

In order to estimate the maximum admissible spacing of the ribs (namely, the minimum number of ribs at different poloidal locations of each VV sector) analytical bending stress calculations were carried out considering a reference coolant pressure of 3.15 MPa at 200°C [7] and a shell thickness of 60 mm as in the ITER VV.

In short, given the maximum admissible bending stress see eq. (1), the maximum distance between the ribs can be defined. Input design data are summarized in table 1.

Table 1 Input data

Coolant Pressure	3.15 MPa
Membrane stress limit (S_m)	130 MPa
Shell Thickness	60 mm
Standard Ribs Thickness	40 mm
Operating Temperature	200°C
Material	AISI 316 L(N)

According to RCC-MRx nuclear codes **Error! Reference source not found.**, the primary membrane plus bending stress shall not exceed $1.5 \cdot S_m$:

$$P_m + P_b \leq 1.5 \cdot S_m \tag{1}$$

where P_m is the primary ***membrane stress*** and P_b is the primary ***bending stress***.

The yield strength of AISI 316L(N) at 200°C is **Error! Reference source not found.**:

$$S_m = 130\ MPa \tag{2}$$

Thus, since P_m is negligible in the case at issue, relation (1) can be written as:

$$P_{b\max} = 195\ MPa \tag{3}$$

Due to the symmetry of loads and geometry, the structure shown in figure 1 can be conceived as an over-constrained beam (see **Figure 3**), that is loaded with a distributed load q

$$q = p \cdot B \tag{4}$$

where B is the developed length of a single shell element.

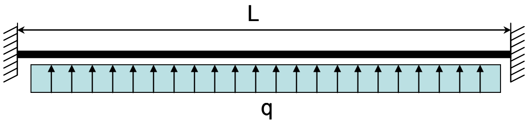

Figure 3 equivalent static scheme of shell structure

As is known, with reference to the static scheme shown in Figure 3, the maximum bending moment on the shell is reached at the ribs position and it is given by:

$$M_{\max} = \frac{qL^2}{12} = \frac{pBL^2}{12} \tag{5}$$

In **Figure 4** the bending moment distribution based on these analytical formula is shown.

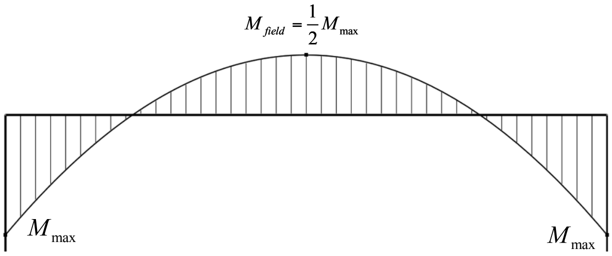

Figure 4 Bending moment diagram on the shell due to coolant pressure

The maximum allowable distance between to ribs can be determined considering the relation:

$$P_{b\max} = \frac{M_{\max}}{J}\frac{H}{2} \tag{6}$$

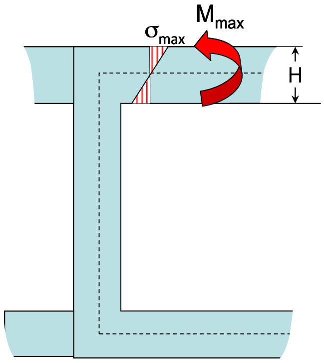

Figure 5 - Stress distribution across the shell at rib position

Where H is the thickness of the shell and J is *moment of inertia* of its section (see Figure 5). For rectangular-shaped sections:

$$J = \frac{BH^3}{12} \tag{7}$$

Thus, substituting equations (4), (5) and (7) into (6) we get:

$$P_{b\max} = \frac{1}{2} p \left(\frac{L}{H}\right)^2 \tag{8}$$

As expected, given the operating pressure p, L/H ratio of shell and ribs structure can be written just as:

$$\frac{L}{H} = \sqrt{2\frac{P_{b\max}}{p}} \tag{9}$$

Finally, using input data in Table 1, we get the maximum width of a single shell on the equatorial plane:

$$L = 667mm \tag{10}$$

It is worth noticing that this value must be increased with the ribs' thickness which has been neglected till now. Therefore, the maximum allowable distance between two ribs is:

$$L_{ribs} = 707mm \tag{11}$$

3. Design of Vacuum Vessel sector

Basing on the maximum allowable distance between ribs (667 mm), the actual design of the entire VV internal structure has been carried out.

The software used for CAD design was CATIA V5. The design activity followed the task guidelines for design and analysis of DEMO vacuum vessel [6]. Moreover, a parametric approach has been adopted in view of the possible changes in VV design after structural analyses and other iterations.

The reference load specifications are reported in [3] and [7].

The VV has been modeled as a surface geometry, rather than a 3D solid body. In other words, just the profiles of the structure have been modeled in CAD environment, while the actual thickness of shell and ribs will be made explicit at the time of later FEM analyses (Figure 6).

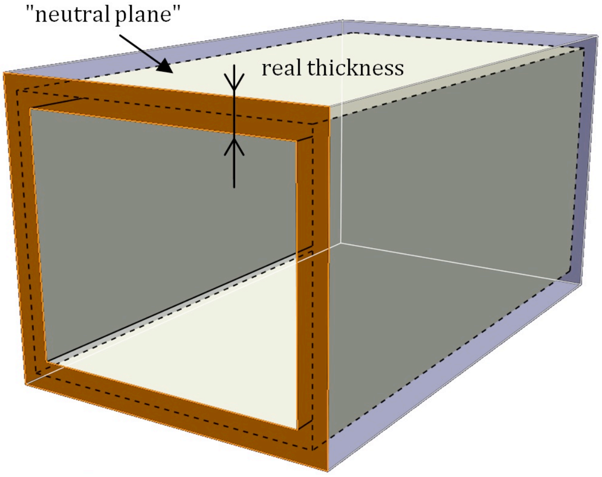

Figure 6 - Surface model correspondent to a thick structure

Given the well-known assumptions of Kirchhoff–Love theory of plates [9], which suitable for the purposes of this analysis, shell models have two advantages over solid models:

- Meshing of surface models is less time-consuming than the one of solid models,
- Wall thickness can be changed in FEM environment without building up a new 3D model and thus a new 3D mesh.
- Significant reduction of degrees of freedom in the FE model

The design of the main components of the VV is being discussed in more details in the following sections.

3.1. Main Vessel

The modeling of the main vessel structure started from two reference surfaces corresponding to the inner and the outer side of the vessel respectively (see **Figure 7**). This reference model was provided by the EUROfusion Program Management Unit (PMU) **Error! Reference source not found.**. In particular, all surfaces have been obtained by the revolution of single-curvature profiles drawn on a poloidal plane around the symmetry axis of the torus, except at inboard side, where both inner and outer surfaces are cylindrical and thus have a single curvature on any toroidal plane and no curvature at all on any poloidal plane.

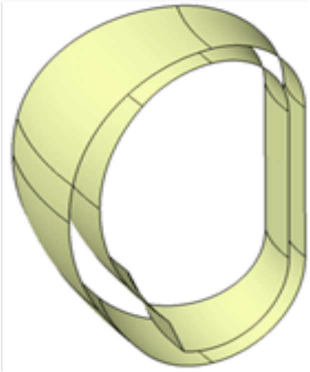

Figure 7 Inner and outer reference surfaces for main vessel

An accurate study of layout for ribs allowed defining datum planes and angles on which the ribs had to be placed. It is understood that ribs profiles are given by intersection between ribs reference planes and the mentioned reference surfaces, while shells are the parts of reference surface between two consecutive ribs.

The VV has a torus shape and therefore the arc length of the walls at *inboard* and *outboard* sides of VV torus is different. For this reason, with reference to any vessel sector, while eleven ribs were placed on its outboard side, only five ribs were put on the other side (**Figure 8**). Moreover, the choice of ribs reference planes had to respect the following conditions [6]:

- Ribs should be as close as possible to the center line of the five *breeding blanket segments* [6]

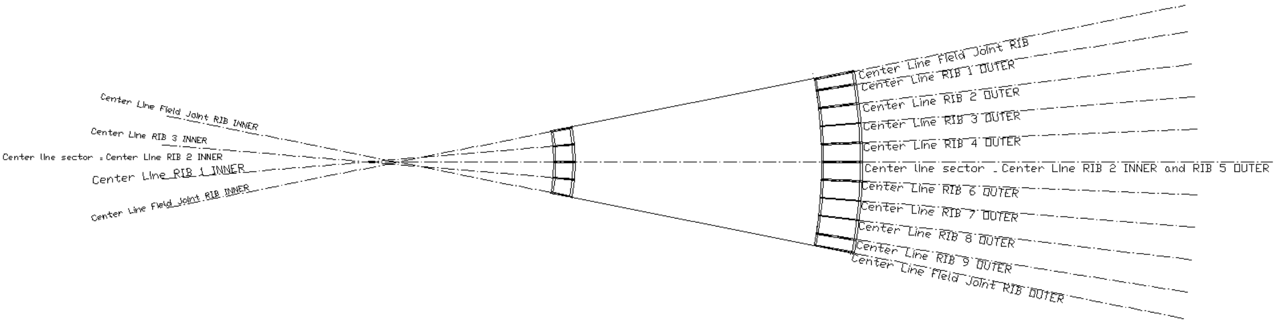

Figure 8 Ribs and shell layout of DEMO single sector

- All ribs must be symmetrical to the center line of the sector, where there should be a rib
- The ribs at the two sides of each sector must be 165mm off the symmetry line between two VV sectors to provide space for an ITER-like splice plate at the field joint..

All ribs are 40mm thick except the poloidal ribs number 2,3,7,8 (see figure 8) on the outboard that are 80mm thick. These ribs are aligned and joined with *gusset plates* that support equatorial and lower ports. This choice guarantees the structural continuity in order that loads can be safely exchanged between ports and main vessel [10]. The gusset plates are 100mm thick and are joined with the sidewalls of the ports through machined components that have been modeled as two short ribs (see Figure 9).

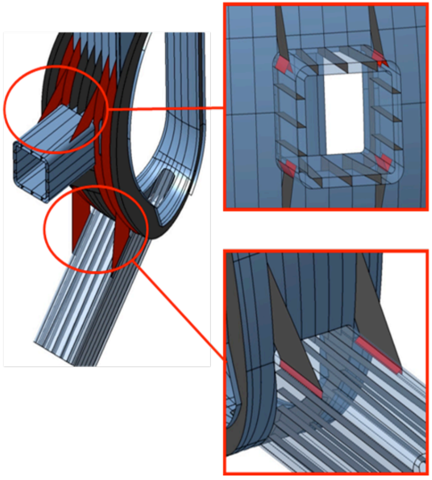

Figure 9 Gusset plates aligned with the corresponding ribs

Given the shape of the vessel sector four short poloidal ribs have been added both at top and bottom of the inboard segment (see **Figure 10**), in order to keep the ribs spacing less than 667mm everywhere. These ribs are joined together through one toroidal rib. Also in this case the poloidal ribs at the inboard side are aligned with the poloidal ribs at the outboard side.

Finally, each shell connecting two adjacent ribs was modeled 60mm thick. The shells do not follow the reference surface exactly. The final surface is in fact mostly faceted because single-curvature shells have been used rather than double-curvature ones mainly for technological feasibility reasons, except with reference to top and bottom surfaces at inboard side, where the double-curvature has been kept

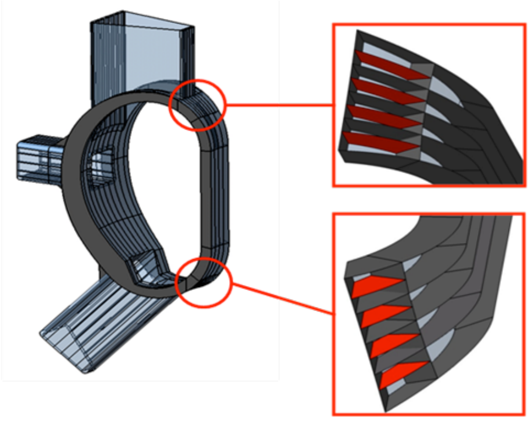

Figure 10 Poloidal ribs on the inboard segment

3.2. Upper Port

The upper port sidewalls lying on poloidal planes are single-walled and welded to both inner and outer shells. The cooling concept of these sidewalls will be studied in the near future. Instead, both the walls facing the inboard and the outboard sides of the VV have the same box structure as the main vessel (see **Figure 11**). The ribs are aligned to those of the main VV and are parallel to longitudinal axis of the port. This ensures a structural continuity between the upper port and the main vessel.

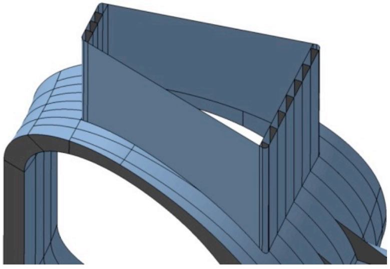

Figure 11 Upper port

One toroidal rib has been placed inside the main vessel and aligned with the outer shell of the upper port, as shown in **Figure 12**.

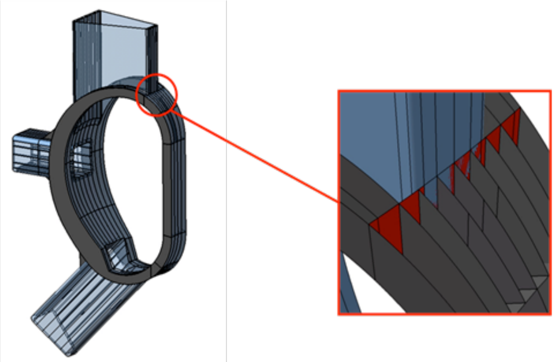

Figure 12 Toroidal rib aligned to the outer shell of the upper port

3.3. Equatorial Port

The equatorial port was modelled using a double walled structure with ribs and shells. In particular, three ribs have been provided for each sidewall. The ribs inside the top and bottom walls are aligned to the ribs of the VV, while the ribs inside the other two walls of the port are parallel to the vessel equatorial plane (**Figure 13**).

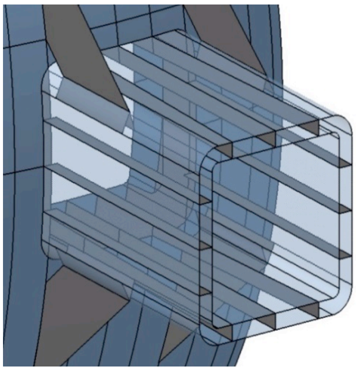

Figure 13 3D model of the equatorial port

3.4. Lower port

The lower port has the same box structure as the equatorial port. The ribs inside the walls of the port shown oblique in the figure are perpendicular to the inner and outer shell and parallel to each other. On the top and bottom the ribs are aligned with VV ribs (**Figure 14**).

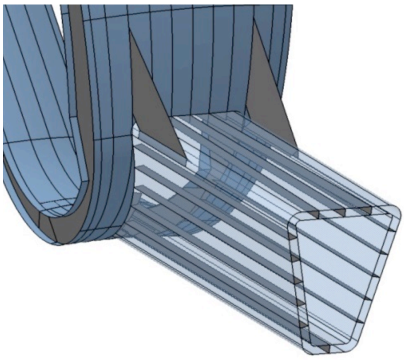

Figure 14 3D model of lower port

3.5. Supports

At the current stage, a simplified design of the DEMO VV supports has been considered to provide a coherent model for structural analyses. Several configurations have been provided, considering supports located either at the lower port or at the equatorial port. Different radial locations of the supports were assessed. Each support is considered welded to the sidewall of the corresponding port (**Figure 15**).

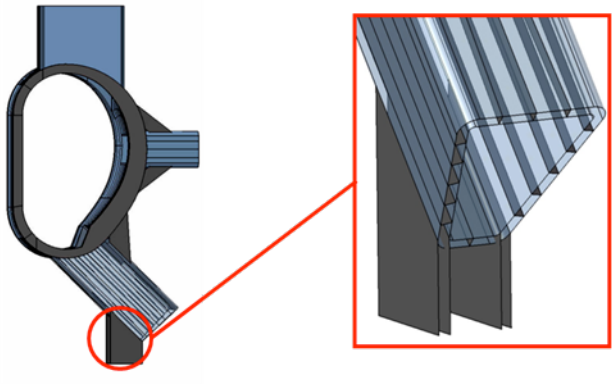

Figure 15 Supports on the lower port jointed to the four port sidewalls

4. Conclusions and future work

A CAD model of a DEMO VV sector has been developed in accordance with DEMO design guidelines. The minimum space between the ribs of VV box structure has been determined in compliance with RCC-MRx . Moreover, a surface modeling technique has been implemented in view of the first FEM analyses based on "shell elements".

The parametric approach used for computer-aided design of the VV makes any change to vessel shape or its internal structure easy to implement. This aspect has a huge impact especially in a conceptual design phase when the number of design changes is expected very high.

Future work will focus on more detailed structural analyses on the developed VV model and its support structure, according to RCC MRx rules.

Acknowledgements

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