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Preliminary Design and Structural Analyses of DEMO Bioshield Roof

Łukasz Ciupiński[a*], Piotr Marek[b] and Christian Bachmann[c]

[a]Faculty of Materials Science and Engineering, Warsaw University of Technology, Woloska 141, 02-507 Warsaw, Poland
[b] Faculty of Power and Aeronautical Engineering, Warsaw University of Technology, Nowowiejska 24, 00-665 Warsaw, Poland
[c] EUROfusion - Programme Management Unit, Garching, Germany

**Corresponding author: lukas@inmat.pw.edu.pl*

The bioshield is a reinforced concrete structure encasing the cryostat that fulfils three main functions: reduce the gamma radiation level to allow man access to external areas, provide access to the cryostat, and – as part of the tokamak building structure – provide support to the equipment and building structures on top of the bioshield roof. The bioshield roof may or may not have the additional function of supporting the cryostat top lid against external or internal pressure loads. Both the cryostat top lid as well as the bioshield roof must provide access to the vertical ports, i.e. large trapezoidal openings that are closed during plasma operation. Bioshield plugs must be inserted to maintain the bioshield's function to protect the area above against radiation exposure. In addition, in case of a major failure in the early operational phase the bioshield roof shall be removable to allow full access to the tokamak via the overhead crane.

The paper presents the results of the first ever design study of the DEMO bioshield roof. The circular symmetry roof construction that is a steel structure with concrete inserts arranged in three peripheral rows to allow full access to the tokamak via the overhead crane has been proposed. Using a flexible beam model, a number of options for the structural concept of the bioshield roof have been assessed. It has been proven that concepts with 16 innermost shield plugs as well as one innermost opening / plug are structurally feasible. The importance of the upper and lower toroidal girders of the steel load bearing structure has been identified. A mass assessment has shown that the weights of all parts of the bioshield roof are well within the lifting capacity of the overhead crane.

Introduction

An important objective of the EU fusion roadmap [1], presented in November 2012 as the key strategic orientation document for the EU Fusion Research Programme of Horizon 2020, is to lay the foundation of a Demonstration Fusion Power Reactor (DEMO) to follow ITER, with the capability of generating several 100 MW of net electricity to the grid and operating with a closed fuel-cycle by

2050. In order to realize the strategy, set out by the Roadmap, EU has funded an EUR multimillion research programme implemented jointly by all European Fusion Laboratories under the COFUND (European Joint Programme) scheme – EUROfusion [2].

DEMO is presently in a pre-conceptual design phase [3] and the European programme is not the only one. Indeed, many of the countries involved in fusion research already have their own programmes for DEMO. Very recently, at the 2016 SOFT [4] Japan, China, and the EU, collectively representing a significant portion of the global fusion community, reported on their own active DEMO programmes.

The paper presents the preliminary analyses devoted to first ever design study of feasible structural concepts of the DEMO bioshield roof. According to the existing preliminary DEMO plant concept, the bioshield is a reinforced concrete structure encasing the fusion reactor that fulfils three main functions: 1) reduces the gamma radiation level to allow man access to external areas, 2) provides access to the cryostat, and – as part of the tokamak building structure – 3) provides support to the equipment and building structures on top of the bioshield roof. The bioshield roof (Fig.1) must provide access to the reactor's vertical ports. Accordingly, the design includes large cut-outs that are closed during plasma operation by plugs to maintain the bioshield's primary function. In addition, in case of a major failure in the early operational phase the bioshield roof shall be removable to allow full access to the tokamak via partial or complete disassembly of the roof using the overhead crane.

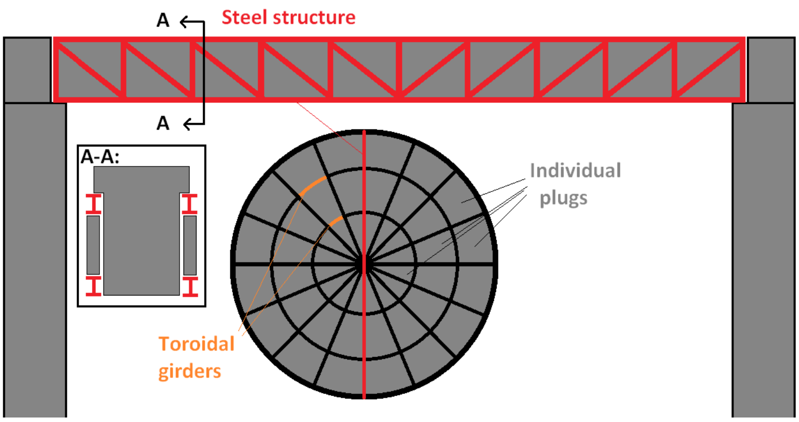


Fig. 1. Sketch of the structural concept of the bioshield roof.

For that analytical assessment, several design requirements have been assumed:

1. The bioshield roof (Fig.1) is supported on the bioshield vertical cylinder that has an inner diameter of ~40m and shall consist of a steel structure with concrete inserts to ensure adequate protection from radiation - minimum concrete thickness shall be 2.5m.
2. Materials: the bioshield is assumed to be constructed with C40/50 concrete and rebars made of BSt500S steel according to Eurocode 2 (EC2) [5]. The supporting structure is constructed of E355 steel and shall be assessed according to Eurocode 3 (EC3) [6].

3. The load case: the bioshield roof is assumed here to support the cryostat top lid. In order to account for the 1 bar differential pressure acting on the cryostat and for the weight of tools using the bioshield roof as floor pressure of 2 bar is considered initially as vertical load on the bioshield roof. That requires satisfying the following criterion [6]: the elastic stress due to the load combination (1.35DW+1.5pres) ≤ f_{yk}/1.1 = 323 MPa. Note: DW = dead weight, pres = pressure.

Analytical assessment

Firstly, an analytical solution is presented that is later on used as guideline for the numerical model. In the proposed design, the steel structure of the bioshield roof consists of a beam and toroidal, circular girders. It supports the concrete blocks that are loaded with gravity and external pressure. Two models can be easily conceived: Model A (Fig. 2a) where the radial beam crosses the central opening of the roof and Model B (Fig. 2b) where the beam is truncated leaving a central opening in the structure.

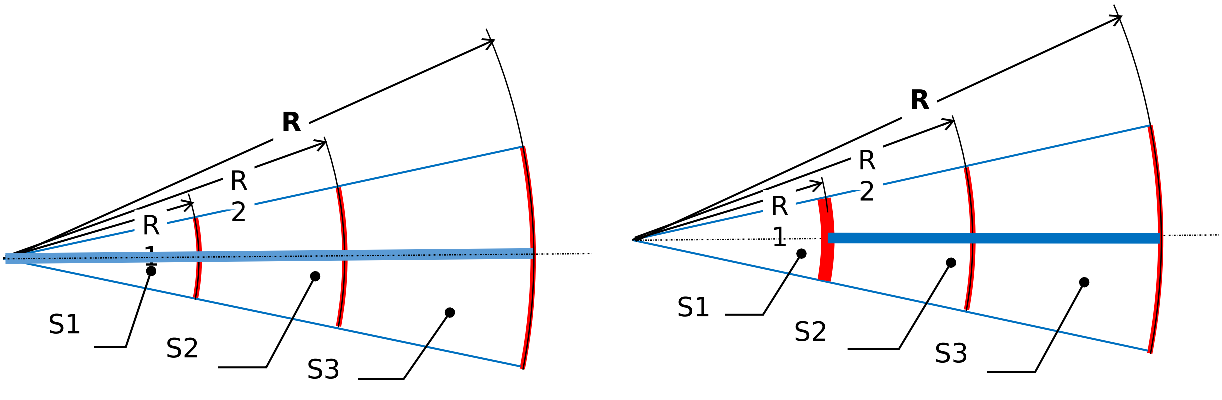


Fig. 2. The general view of the sector (1/16) of the bioshield roof (toroidal girders marked red): a), continuous radial beam – Model A , b) truncated radial beam – Model B. note the.

The mass of the bioshield roof concrete of a 20° sector of the bioshield roof plug is calculated as follows:

$$\mathbf{m} = S \cdot H_{block} \cdot \rho = 78.54\ m^2 \cdot 2.5\ m \cdot 2{,}400\ kg/m^3 = 471\ tons \qquad (1)$$

where: $S = S_1+S_2+S_3$ – the surface areas of the three radial sector of a 20° section of the bioshield roof, see figure 2

H_{block} – the hight / thickness of the concrete blocks

ρ – the concrete density

Thus, the total load for one sector to be supported by the steel structure with the assumed load case is:

$$\mathbf{Q} = 1.35 \cdot 471{,}240 \text{ kg} \cdot 9.81 \text{ m/s}^2 + 1.5 \cdot 0.2 \cdot 10^6 \text{ Pa} \cdot 78.54 \text{ m}^2 = 29.8 \text{ MN} \qquad (2)$$

For both models presented in Fig. 2 a simplified beam model for the radial steel beam can be considered. In the case of innermost plugs replaced by a single central one the truncated radial beam should be restrained with possibly two toroidal girders (Model B in Fig.2b). The simplified model for this case can be constructed as follows (Fig.3a, b).

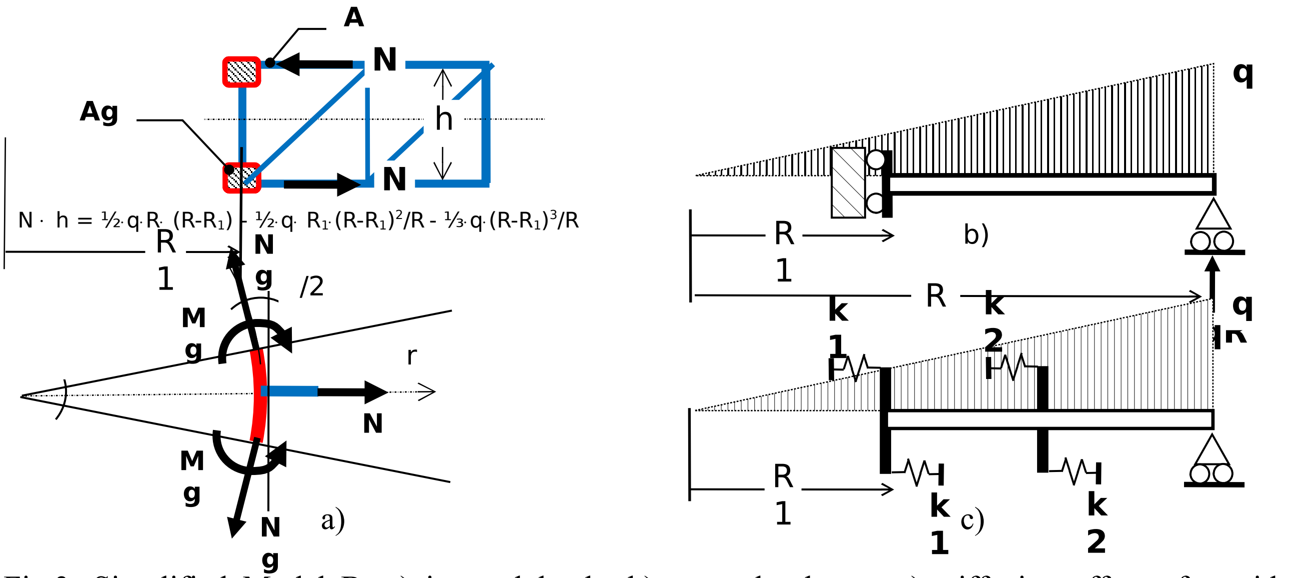


Fig.3. Simplified Model B: a) internal loads, b) general scheme, c) stiffening effect of toroidal girders (A – beam cross section, A_g – girder cross section, N – forces, M – moments, h – beam web height).

Assuming R_1=7.5 m = 0.375·R and using the expression for maximum bending moment in the beam, we calculate the minimum cross sections of the radial beam and central toroidal girders that satisfy the EC3 as follows:

$$\mathbf{A}^{\mathbf{min}} \geq 0.1579 \cdot q \cdot R^2/ (h \cdot f_{yk}/1.1) \qquad (3)$$

$$\mathbf{A}_{\mathbf{g}}^{\mathbf{min}} \geq 0.4047 \cdot q \cdot R^2/ (h \cdot f_{yk}/1.1) \qquad (4)$$

Then for the beam web span of h = 3.5m we have: $\mathbf{A}^{\mathbf{min}} = 0.1666 \text{ m}^2$ and $\mathbf{A}_{\mathbf{g}}^{\mathbf{min}} = 0.4269 \text{ m}^2$.

The model presented above is valid when the inner toroidal girders are stiff whereas others are relatively weak (Fig. 2b). The effect of toroidal girders can be described then as elastic supports of given stiffness k_1, k_2 (Fig. 3c). The effect of these additional supports on the presented model would of course depend on the parameters of the girders assumed. This effect is studied in the FE analysis presented further.

Finite Element Models

The FE analysis was performed using ANSYS ® Mechanical APDL v.15 [7].

An initial FE model was built to assess the approximate geometry parameters of the steel structure.

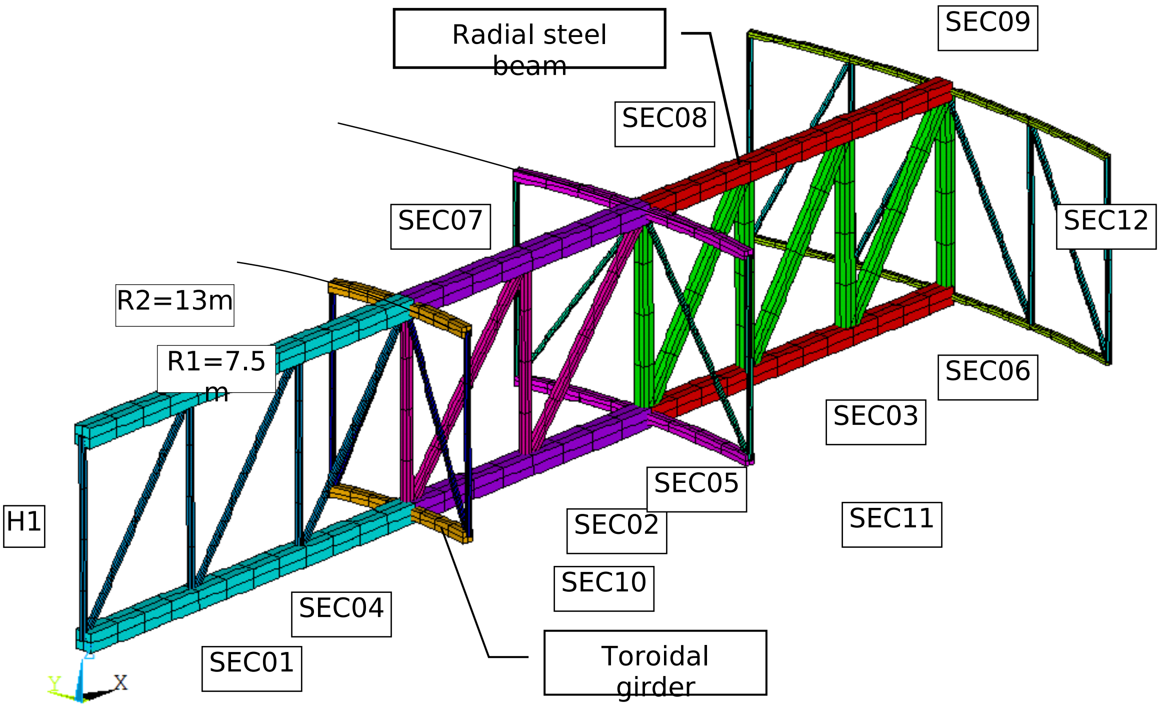


Fig. 4. Initial FE model used to study the effective steel structure configuration.

The model consisted of beam188 elements and the concrete blocks were modelled using solid45 elements. Contact elements (CONTA178) were used to simulate interaction between concrete blocks and beams. Cross-section parameters were applied for given parts of the steel structure (SEC01, SEC02, etc.) according to Fig.4. Symmetry boundary conditions were applied. Alternative models were studied using different configurations of toroidal girders and struts. The rectangular cross-section shape of all beams was assumed initially. The preliminary calculations have shown that Model B with top and bottom girders without trusses should be further developed. Vertical displacements and axial direct stress in steel structure were examined (Fig.5).

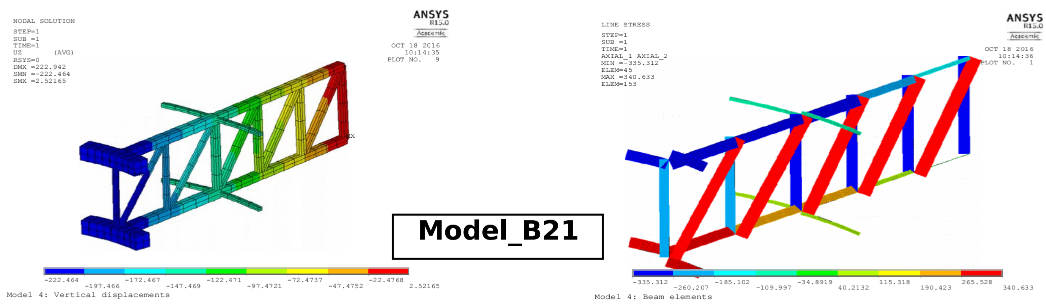


Fig. 5. Vertical displacements and axial direct stress in steel structure of Model_B21

Three configurations were studied: 1) thick inner toroidal girders (Model B21), 2) moderate inner and outer toroidal girders (Model B22) and 3) thicker outer toroidal girders (Model B23). Table 1 contains cross-section areas and axial stress ranges for the configurations with minimum masses.

Table 1. Optimal cross-section areas and axial direct stress range in beams (H1=3.5 m)

Model		SEC02	SEC03	SEC05	SEC06	SEC07	SEC08	Mass [t]
B21	**A** [m²] **Smin/Smax** [MPa]	0.156 -319/283	0.115 -335/227	0.031 -246/330	0.066 -290/341	0.424 -301/301	0.030 -101/96	**66.700**
B22	**A** [m²] **Smin/Smax** [MPa]	0.090 -312/259	0.120 -322/219	0.031 -250/325	0.066 -291/343	0.250 -288/300	0.250 -237/225	**71.199**
B23	**A** [m²] **Smin/Smax** [MPa]	0.075 -303/241	0.120 -321/220	0.030 -250/322	0.065 -291/343	0.200 -291/309	0.300 -243/231	**71.605**

Table 2. Steel beam cross-section dimensions as in the final beam model

Parameters	SEC02	SEC03	SEC05	SEC06	SEC07	SEC08	SEC09	SEC10	SEC11	SEC12
B [mm]	500	450	200	300	800	600	350	250	150	350
H [mm]	800	800	300	400	800	800	800	800	800	350
T [mm]	80	80	50	80	155	80	80	80	80	100
G [mm]	80	80	50	80	200	80	80	80	60	100
A [m²]	**0.1312**	**0.1232**	**0.0300**	**0.0672**	**0.346**	**0.1472**	**0.1072**	**0.0912**	**0.0624**	**0.085**

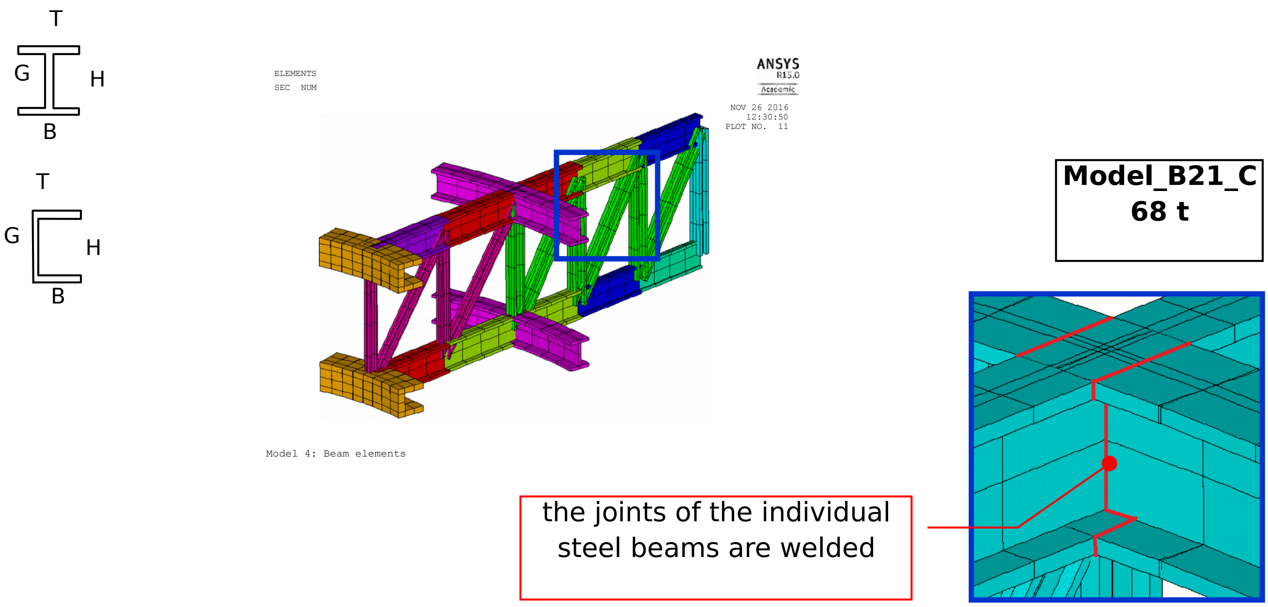
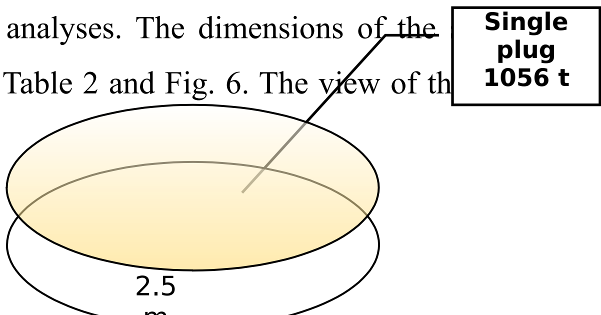
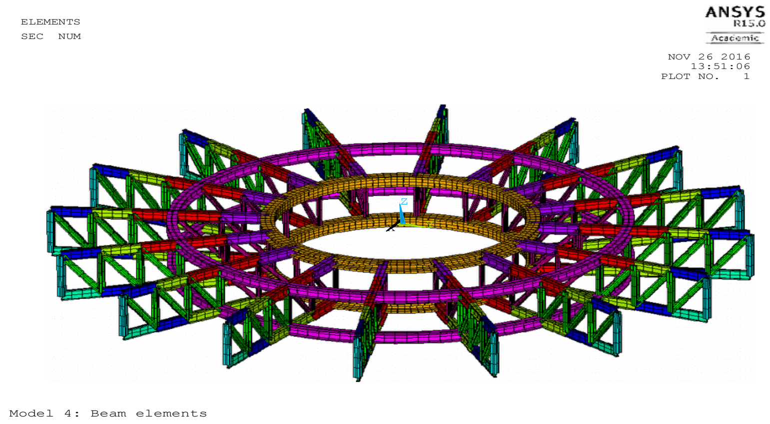


Fig. 6. Final FE beam model of Model_B21_C

The shape of inner girders cross-section was changed to box shape and all other steel beams into “I” shape while keeping the optimum cross-section areas of case B21 (Table 1). Afterwards, different options of inner girders cross-section shape were evaluated keeping the girder cross-section area constant, A_g = const. Apart from the box shape, the “C” and “I” shapes were studied. The “C” shape was chosen based on those analyses. The dimensions of the th that new cross-sections geometry are presented in Table 2 and Fig. 6. The view of th structure based on



the final FE beam model is shown in Fig. 7.



1088 t (steel structure) **+ 1376 t** (concrete inserts)

Fig. 7. View of the complete bioshield roof structure (the concrete inserts and plugs are omitted for image clarity except the central plug).

Discussion

Using both the simplified analytical models and FE models the preliminary design of the DEMO bioshield roof has been verified against the structural design criteria.

Exploiting the simplified analytical models was efficient to predict the minimum cross-sections parameters as well as to identify the importance of the toroidal girders. The FE models allowed a suitable sizing of the individual members of the structure. Using a flexible beam model, a number of options for the structural concept of the bioshield roof have been assessed. The structure is based on large radial steel frameworks toroidally connected by girders. Concrete plugs are inserted into the interspaces between the steel beams and concrete inserts fill-in the gaps in the steel frameworks. It is possible to make the bioshield roof structure both with continuous radial beam as well as with a truncated one (see Fig. 2). It was found that, with a large opening in the centre, the structure works effectively (Fig.6). Moreover, the analyses of the interaction of the concrete plugs with the steel supporting structure showed that although the concrete plugs were supported along their edges, the load, in fact, was transmitted in their corner regions due to the high stiffness of the plugs.

Furthermore, the results have shown that the lower toroidal girders are necessary. With all the dimensions and vital structural elements, it was then possible to assess the total mass of the roof and to propose the assembly sequence for it. It was concluded that the entire steel structure with the concrete inserts can be assembled in the assembly hall and then be transported to the tokamak pit using the DEMO overhead crane (the mass of the steel structure including concrete inserts in –

between the steel members for radiation shielding is estimated to be 2464 tons). Also, the inner plug (1056 tons) and the plugs above the vertical ports (<200 tons each) and the outermost plugs (<200 tons each) can be lifted.

Conclusions

The first ever design study of feasible structural concepts of the DEMO bioshield roof have been successfully performed. Using a flexible beam model, a number of options for the structural concept of the bioshield roof have been assessed. The circular symmetry roof construction that is a steel structure with concrete inserts arranged in three peripheral rows to allow full access to the tokamak via the use of the overhead crane and partial or complete roof disassembly has been proposed. It has been proven that concepts with 16 innermost shield plugs as well as one innermost opening / plug are conceivable. The proposed structure could be assembled using the postulated DEMO overhead crane with a lifting capacity of ≥3,000 tons.

Acknowledgments

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