Limit Analysis for the Mechanical Structure of the ITER Neutron Shielding Block

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Abstract The ITER neutron shielding blocks are located between the inner shell and the outer shell of the vacuum vessel (VV) with the main function of providing neutron shielding. Considering the combined loads of the shielding blocks during the plasma operation of the ITER, limit analysis for one typical ferromagnetic (FM) shielding block has been performed and the structural design has been evaluated based on the American Society of Mechanical Engineers (ASME) criterion and European standards. Results show that the collapse load of this shielding block is three times the specified load, which is much higher than the design requirement of 1.25. The structure of this neutron shielding block has a sufficient safety margin.

Keywords: ITER, VV, neutron shielding blocks, limit analysis, criterion

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1 Introduction

The VV is an important component in a tokamak to provide a high quality vacuum for plasma experiments. For ITER, the first large-scale fusion tokamak, the VV is torus-shaped, made of stainless steel with a double, ribbed shell filled with shielding and cooling water between two shells (inner shell and outer shell) [1].

Neutron shielding blocks, including FM blocks and non-FM blocks, are used to fill the space between the two shells of the VV to provide neutron shielding for ITER. FM blocks with ferromagnetic plates used in the shadow of the TF coils in the outboard area can also reduce the toroidal field (TF) ripple. During the operation of ITER, neutron shielding blocks will be subjected to combined loads, including preloading for bolts, inertial loads caused by accelerations due to gravity, seismic events and the transient motion of the VV during vertical displacement events (VDE), and electromagnetic (EM) loads due to eddy current and magnetization [2]. These loads have a strong impact on the structure of the shielding blocks, so evaluations by analysis become necessary.

A simple elastic analysis for one typical FM block in the outboard region had been made, but the primary stress and primary stress plus bending stress exceeded the design allowable limit. To obtain the real margin of the structure, this paper reports the limit analysis for this block.

2 Design of neutron shielding block

Neutron shielding blocks are located in the space between the inner shell and outer shell of the VV (Fig. 1), occupying about 60% of the space. There are two types of shielding blocks, the primary shielding block using material SS304B7 (with 2%-2.25% boron) and SS304B4 (with 1%-1.25% boron) provides effective neutron shielding while ferromagnetic shielding blocks made of material SS430 provide neutron shielding and reduce the toroidal field ripple. The shielding blocks contain several individual shielding plates with a thickness of 40 mm which are bolted together by bolts M30.
The length of the shielding plates is normally less than 0.3 m poloidally and less than 0.15 m toroidally. The shielding blocks are supported by upper brackets and lower brackets attached to the ribs of the VV and positioned with bolts M20/24 to withstand the mechanical forces. The connecting bolts, nuts, washers and spacers are made of XM19, while the VV shells and ribs are made of 316L (N)-IG[3,4]. All components of the shielding block are shown in Fig. 2.

![Shielding block components](color online)

Fig. 2  Shielding block components (color online)

3 Description of load on neutron shielding block

According to ITER load specifications, neutron shielding blocks are operated under various types of mechanical load, which can be divided into three independent categories: preloading of bolts, inertial loads, and EM loads. The inertial loads are caused by accelerations due to gravity, seismic events and transient motion of the VV. The EM loads, which include eddy current loads (during the movement of plasma, e.g. VDE is included) and magnetization loads, are normally a strong design driver and act upon nearly all conductive structures during transient events.


Gravity: gravity loads occur due to masses that are accelerated by gravity. An acceleration of 9.81 m/s² must be applied on all components of shielding blocks in the vertical direction.

Seismic loads: since the neutron shielding blocks are fixed together with the VV, the seismic loads of the VV must be applied to the shielding blocks.

Dynamic loads from the VV during VDEs: during operation, the transient motion of the VV due to VDEs will apply dynamic loads to the shielding blocks. The dynamic loads are applied with accelerations in three directions of the VV global coordinator system for this static analysis.

According to the VV load specification, the recommended accelerations of inertial loads for the shielding block are shown in Table 1.

<table>
<thead>
<tr>
<th>Inertia load</th>
<th>Radial accelerations (m/s²)</th>
<th>Toroidal accelerations (m/s²)</th>
<th>Vertical accelerations (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>0</td>
<td>0</td>
<td>9.81</td>
</tr>
<tr>
<td>SL</td>
<td>1.428</td>
<td>0.826</td>
<td>8.126</td>
</tr>
<tr>
<td>Dynamic loads during VDEs</td>
<td>5.2</td>
<td>5.8</td>
<td>3.2</td>
</tr>
</tbody>
</table>

EM loads due to the eddy current: the eddy current EM loads of the shielding blocks are calculated based on the existing analysis results of two shielding blocks for a VDE fast downward load case. The recommended values of the eddy current EM loads are shown in Table 2.

<table>
<thead>
<tr>
<th>Eddy current force</th>
<th>F_rad (N)</th>
<th>F_tor (N)</th>
<th>F_pol (N)</th>
<th>M_rad (N·m)</th>
<th>M_tor (N·m)</th>
<th>M_pol (N·m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eddy</td>
<td>13050</td>
<td>2640</td>
<td>14874</td>
<td>4032</td>
<td>1437</td>
<td>10484</td>
</tr>
</tbody>
</table>

EM loads due to magnetization: FM blocks consisting of ferromagnetic plates will be magnetized by the external magnetic field during operation. The magnetization EM loads are obtained through the analysis considering TFC, PFC, plasma and ELM/VS coils and always exit in the operation phase. The maximum magnetization EM forces with the force of 30 kN, 152 kN and 42 kN in three directions are selected from all FM insert blocks, which can be applied in the structural analysis for all FM blocks[2,5].

4 Limit analysis of the neutron shielding block

4.1 Limit analysis and applicable criterion

Limit analysis is a special case of plastic analysis, which assumes an ideal elastic-perfectly plastic material model and infinitesimal strain theory. An elastic-perfectly plastic material model is shown in Fig. 3. With the increasing of the mechanical load, the material exhibits linear elastic behavior up to the yield stress \( \sigma_y \), after which unlimited plastic flow or perfect plasticity occurs. In the limit analysis, the equilibrium and flow characteristics at the limit state are used to calculate the collapse load. If, for a given load, any system of stresses can be found which satisfies equilibrium everywhere, and exceeds the material yield strength nowhere, the load is at or below the collapse load. This is the lower bound theorem of the limit analysis which permits calculations of a lower bound to the collapse load (herein also defined as the limit load).
For the traditional elastic analysis, the allowable load is calculated indirectly by partitioning the elastic stress into primary, secondary and peak categories and limiting the primary stress to a specified allowable value. Stress categorization is probably the most difficult aspect of the elastic design by using the analysis procedure and has become increasingly more difficult as stress analysis techniques have advanced. When the design is based on a limit analysis, the allowable load is determined directly from the elastic-plastic response of the object.

As it is written in ASME section 3, the limits on local membrane stress intensity and primary membrane plus primary bending stress intensity need not be satisfied at a specific location if it can be shown by means of limit analysis or by tests that the specified mechanical loadings do not exceed two-thirds of the lower bound collapse load \([6,7]\). For limit analysis, load factor \(LF\) is defined as:

\[
LF = \frac{C_i}{C_L},
\]

(1)

where \(C_L\) is the mechanical load concerned (fixed for a specific operate condition) and \(C_i\) is the increased load during the analysis. As specified mechanical loading must not exceed two-thirds of the limit load:

\[
C_L < k \times \frac{2}{3} C_{\text{lim}},
\]

(2)

where \(C_{\text{lim}}\) is the limit load and \(k\) is the stress intensity factor.

Considering the above two equations, the criterion of the limit analysis can be deduced:

\[
LF_{\text{collapse}} = \frac{C_{\text{lim}}}{C_L} > \frac{3}{k \times 2},
\]

(3)

where \(LF_{\text{collapse}}\) is the load factor at collapse. In this analysis including a seismic load, the factor \(k = 1.2\) is chosen \([6,8,9]\). So the criterion is that \(LF_{\text{collapse}}\) must be above 1.25.

### 4.2 Description of the finite element model

The finite element (FE) model includes shielding plates, an upper bracket, a lower bracket, bolts, washers and spacers. The FE model of these components is shown in Fig. 4. It has 330012 nodes and 83656 elements including 15640 contact elements. A higher-order 3-D 20-node structure solid element SOLID186 has been chosen for all the components. A pair of 3-D 8-node surface-to-surface contact elements, TARGE170 and CONTA174, has been selected to simulate the friction between the different components. Standard contact with a friction ratio 0.25 between brackets and plates has been modeled as well as bonded contact has been used between M24/Rib, M30/nuts and M30/lower bracket to model the thread. The preloading of bolts has been applied via element PRETS179. The thickness of the shielding plates is 40 mm, the rib is also 40 mm, the spacer is 4 mm, and the washer is 4 mm or 1 mm at different locations. Adopting a conservative assumption, bolts have been modeled using their minor diameter. M30 minor diameter is \(\phi 26.2\) mm. M24 minor diameter is \(\phi 21.2\) mm.

### 4.3 Boundary conditions

The assembly procedure of a block with three plates is shown as an example in Fig. 5. Preloading is applied in two steps. Firstly, the preloading is applied on bolts M30 in order to compress the plates. In this step, preloading will not produce a bending for the rib. For analysis, to take into account the assembly procedure and avoid bending the rib, the FE model of the rib has been split into 2 parts, with a 5 mm gap. From the results of preloading bolts M30, an average of the radial displacement of the rib is obtained (0.0668 mm) and set as a boundary condition. The other boundary conditions setting edges and areas fixed to the rib are not considered in this analysis (Fig. 6).
4.4 Material properties

According to ASME section III, for the limit analysis an elastic-perfectly plastic behavior has been used for 316L (N)-IG, SS430 and XM19 with the yield strength \( R_L = 1.5 \) Sm, where Sm is the allowable stress of material. The ANSYS bilinear isotropic option (BISO) has been chosen to represent the material behavior. The elastic-perfectly plastic models are shown in Fig. 7. This analysis assumes that the material properties would not be changed after the irradiation of neutrons. The material properties with a temperature of 110°C in the operation conditions are shown in Table 3.

Table 3. Material properties used for limit analysis

<table>
<thead>
<tr>
<th>Material</th>
<th>316L (N)-IG</th>
<th>SS430</th>
<th>XM19</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young modulus (MPa)</td>
<td>193000</td>
<td>195000</td>
<td>190000</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>7919</td>
<td>7682</td>
<td>7880</td>
</tr>
<tr>
<td>Friction ratio</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Allowable stress (MPa)</td>
<td>147</td>
<td>127</td>
<td>225</td>
</tr>
<tr>
<td>Yield stress ( R_L ) (MPa)</td>
<td>220</td>
<td>195</td>
<td>338</td>
</tr>
</tbody>
</table>

5 Results of the limit analysis

To determine the plastic limit load, two methods are used (shown in Fig. 8). The twice-elastic-slope (TES) method, written in ASME section III, defines the limit load at the intercept of a line drawn from the origin of a load-deformation curve at a slope of twice the slope of the elastic portion of the curve \([6,10]\). The tangent-intersection (TI) method is used in the European Standard, where the limit load is determined as the ordinate of the point of intersection of the starting linear section and the tangent drawn to the section of the curve that characterizes the plastic deformation \([11,12]\).

The limit analysis is performed by using the finite element program ANSYS. The applied load is increased step by step. To decide whether the lower bracket or upper brackets have reached their limit load, the averaged Von Mises (VM) stresses on the brackets are calculated at each load step of the increased load (Fig. 9) by defining paths at the section of the higher stress region (Fig. 10(a) and (c)) until the shutdown of the analysis. As is shown in Fig. 9, when the solution time step is more than 6, the material of brackets reaches yield and the average stress becomes stable. Since the first two time steps is used for preloading the bolts M30 and M24, when the time step is 6, the load factor is 4, the bracket material reaches yield and the average stress...
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becomes stable. Defining the contour of the stresses of the lower bracket and upper bracket at 220 MPa, it can be found that a large amount of region is yielded. In this phase, a small increment in the load will cause an unlimited increase in deformations. The VM strain of the brackets at the last converged sub step is shown in Fig. 10 (b) and (d). Choosing the nodes which have the maximum values of VM strain and reading the values of each load step, the VM strain of the brackets and plates is obtained at each step and the LF-VM strain curves are drawn as shown in Fig. 11. Through the method of TES and TI, the LF\textsubscript{collapse} of these components is determined as shown in Table 4.

### Table 4. $L_F$\textsubscript{collapse} of brackets and plates

<table>
<thead>
<tr>
<th>Component</th>
<th>TES</th>
<th>TI</th>
<th>Allowable limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower bracket</td>
<td>3</td>
<td>4.5</td>
<td>1.25</td>
</tr>
<tr>
<td>Upper bracket</td>
<td>3.7</td>
<td>4.4</td>
<td>1.25</td>
</tr>
<tr>
<td>Plates</td>
<td>3.7</td>
<td>4.3</td>
<td>1.25</td>
</tr>
</tbody>
</table>

*Fig. 9*  Averaged Von Mises (VM) stress on brackets at each load step (color online)

*Fig. 10* Von Mises stress and strain distribution for brackets (color online)

*Fig. 11* LF-VM strain curves for brackets and plates (color online)
6 Conclusions

Limit analysis has been performed for one typical FM shielding block. Elastic-perfectly plastic behavior has been used for all components. According to the above analysis results, comparing the $L/F_{\text{coll}}$ of the lower bracket, upper bracket and plates, for a conservative assumption, $L/F_{\text{coll}}$ of this shielding block is 3. The safety margin obtained in the limit analysis is 1.75. It shows that the design of this neutron shielding block, which is subjected to a combined load in ITER operating conditions, has enough safety margins. The plastic limit load determined by the TES method written in ASME section 3 is usually lower than the TI method defined in the European Standard. Using the TES method will obtain a conservative result of this limit analysis.

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