DEVELOPMENT AND VALIDATION OF CRYOSTAT
FINITE ELEMENT MODEL WITH UNIQUE FE
METHOD

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Abstract

The ITER Cryostat—the largest stainless steel vacuum pressure chamber ever built which provides the vacuum environment for components operating in the range from 4.5 k to 80 k like ITER vacuum vessel and the superconducting magnets. Although Cryostat Design Model was qualified, but as a Safety Important Class requirement, validation of model at each stage is necessary. The Cryostat is currently at manufacturing stage, frequent changes major/minor are coming during manufacturing process, some of which being judgmental needs fine assessment. Assessing the effect of these changes using the conventional FE method needs significant time and effort. Also the need of iteration for every change further increases the time and effort by manifold in just making FE model. The paper will present a unique method to develop FE model of complex systems like Cryostat and enables to validate the structural strength of the system during any load or load combinations. One can incorporate frequent changes quickly and assess with ease. The paper mainly focuses on the details of the different approach in development of FE model of Cryostat from current manufacturing Model of Cryostat. In this method the context and complexities identified and component wise thirty FE models of Cryostat are generated. Then these FE models are integrated into a full Cryostat (assembly) FE model using suitable contact definitions. This approach facilitates to incorporate component level changes without affecting the whole Cryostat model, thus saving in time and efforts of re-generating the meshed model. Secondly it demonstrates simplification in Cryostat Bearing model. Lastly validation of the analysis result of this FE model with ASME Section VIII Div. 2 and with previous Cryostat assessment. This approach once developed, reduce time and effort drastically which makes iterations easier and hence enables quick decision making for the Design Responsible authority.

1. INTRODUCTION

The cryostat is the very largest component of International Thermonuclear Experimental Reactor ITER. The function of the Cryostat is to provide a vacuum environment to avoid excessive thermal loads from being applied to the components that are operated at cryogenic temperatures. Cryostat Design Model was qualified [1,2] earlier by ITER. As a Safety Important Class system, Design qualification at every change in its development and installation phases is mandatory. The Cryostat systems is currently at manufacturing stage, several Deviation request are being reported e.g. tolerances change, ribs modification etc. These changes affect the behaviour of Cryostat which needs re-assessment. The conventional design approach in Finite Element method (FEM) needs significant time and effort, as incorporation of changes calls for redevelopment of full mathematical model.

In the paper a “unique method” of developing FE model for complex systems like Cryostat is presented, which typically addresses above need and the method is qualified. The conventional FE method of assessment is to develop the mathematical model of single complete Cryostat structure with suitable constraint equations. For any change in the Cryostat geometry the complete procedure of model development is repeated. This unique method involves dividing and meshing of big components into sub components, so the full Cryostat is divided into 30 sub components and mathematical models of these individual components are developed. Then these sub components are integrated using suitable constraint equations to create full FE model. This enables individual stiffness matrices generation for these sub components, rather than generating and working with single stiffness matrix for whole Cryostat. Any individual stiffness matrices for these subs components can be easily modified without affecting other matrices which are coupled using constraint equations. In this unique method, nonlinear components like Bellow and Cryostat bearing are modelled using static equivalent method. Bellsows has three directional stiffness which are modelled with help of spring elements [8] and behaviour of Cryostat bearing is captured by combination of spring and Dashpot in parallel (Bonc-Wen model) [7]. The effective stiffness K (N/mm) and effective damping C (Ns) for bearing calculated [6] as described in Bonc-Wen model.
The complete assembly of Cryostat FE model FIG. 1 is developed and the assembled FE model is validated using already assessed Cryostat engineering model done by ITER. Integrity of model is assessed using modes shapes and first natural frequency is at 5.7 Hz which are in line with ITER results 5.4 Hz. For qualification of developed FE model category II loads with load combination [3, 4] Dead Weight + External Pressure, Dead Weight + External Pressure + SL-1, Dead Weight + Internal Pressure 1.4 bar has been considered. Appropriate boundary conditions are used [1, 2]. Secondary loads such as Thermal loads, Vertical displacement event (VDE) loads, Electro-magnetic (EM) loads have little influence [2] on the Cryostat structure are neglected. The results obtained from developed FE model are in close approximation with results of Cryostat engineering model [1, 2].

As the present need was to address the changes of manufacturing model, so further Cryostat manufacturing FE model is developed with this unique approach. It is then analysed and qualified for category II loading and load combination of Dead Weight + External Pressure + SL-1 and the result are discussed in the paper.

FIG. 1. Cryostat FE Model extracted from CATIA Cryostat in ANSYS Design Modeler.

2. DEVELOPMENT OF FE MODEL OF CRYOSTAT DESIGN MODEL USING UNIQUE METHOD

One of the prime objectives of the paper is to validate the unique approach by developing and validating full Cryostat design using already assessed Cryostat engineering model done by ITER [1, 2]. The full 360° shell model of Cryostat is extracted (shell thickness ~50 mm) wherever possible in design modeler (Ansys v16) [8] from current Cryostat Catia Design V5 Model. Based on the complexity of the components the Cryostat is modelled into four major sections namely Top lid, Upper Cylinder, Lower Cylinder and Base section FIG. 2. These individual sections are meshed and coupled together using appropriate contact definition. Separate “identifier-named selections” or “Tag” has been generated for each connection pair, scoped to connection geometry [8]. Every time a change is incorporated/updated in the generated unique FE Model, the software automatically generates connection between the pairs using these “identifiers-named selections” as reference.

FIG. 2. Cryostat design meshed model and its sub-assemblies

2.1. Validation of developed Cryostat FE Design model developed using unique method

The Model developed with unique approach is validated for category II load with load combination by comparing the results of earlier assessment of cryostat done by normal approaches [1]. A comparison of results is shown in TABLE 1. Integrity of model is assessed using modes shapes and first natural frequency is at 5.7 Hz which are in line with ITER results 5.4 Hz. The comparison shows that the results are in line with the earlier assessment, thus validating the unique approach accuracy in predicting the results.
TABLE 1. Validation of developed Cryostat FE model with earlier assessments

<table>
<thead>
<tr>
<th>Considered results for Assessment</th>
<th>Result in normal approach</th>
<th>Result in new approach</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deflection in base section in Dead weight condition</td>
<td>36.8mm</td>
<td>37mm</td>
<td>Less than 1%</td>
</tr>
<tr>
<td>First Mode of natural frequency</td>
<td>5.7Hz</td>
<td>5.4Hz</td>
<td>Less than 1%</td>
</tr>
</tbody>
</table>

3. DEVELOPMENT OF FE MODEL OF CRYOSTAT MANUFACTURING MODEL USING UNIQUE METHOD

3.1. Methodology for generation of Mathematical model using unique method

Second prime objectives of this assessment is to develop Mathematical/meshed model of full cryostat manufacturing model section wise, which will allow incorporating any further changes without affecting full mathematical/meshed model. Full cryostat model is divided into various sections, depending upon the complexity of geometry. All the sections are individually modelled and meshed with accepted quality level. All the section of cryostat, divided based upon their geometric complexity, are individually meshed using the above mentioned approach. Other interfacing components considered in the assessment were TCPH, HNB/DNB Ducts, gravity support base plates for VV & magnets, toroidal male and female lugs and Cryostat bearings. All the individually meshed models were assembled in subgroups and then to final full cryostat model, by defining contacts via named selection approach [8]. This method of model development is although time consuming, but serves as a platform for future modification at local level, without affecting other sections. The following layout FIG. 3 briefly describes method.

![Diagram of Cryostat model development]

FIG. 3. Methodology for Cryostat model development

3.1.1. Detailed Individual Sections geometry and surface model

TABLE 2. Shows the divisions and individual modeling of Cryostat manufacturing model

<table>
<thead>
<tr>
<th>TABLE 2. Detail modelled sectors of Cryostat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sector</td>
</tr>
<tr>
<td>Top Lid</td>
</tr>
</tbody>
</table>
3.1.2. Meshing of subsection of full Cryostat Model

All the surface/solid models of cryostat are independently meshed with acceptable quality. The sections are “conformal” meshed as far as possible to avoid unnecessary contact elements [8]. The total no of Nodes are 1635055 and elements are 988453. The common interfaces of these sections were assembled into their subgroups using Named Selection Approach. The Cryostat Model contains both solid and shell elements in the present assessment. TABLE 3 shows a detailed breakup of used elements in Cryostat.
### TABLE 3. FE Mesh and Element Types

<table>
<thead>
<tr>
<th>Element type</th>
<th>Nodes</th>
<th>Name</th>
<th>Used in Mesh of</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Shell</td>
<td>4</td>
<td>SHELL181</td>
<td>Cylindrical Shell Structure in Cryostat, Top &amp; Central Lid, Internal &amp; External Ribs, TCPH, Ducts</td>
</tr>
<tr>
<td>Structural Solid</td>
<td>20</td>
<td>SOLID186</td>
<td>Shielding Blocks, Cryostat Bearings, Toroidal Lugs</td>
</tr>
<tr>
<td>Mass Element</td>
<td>1</td>
<td>MASS21</td>
<td>Lumped Mass for UTS and LTS</td>
</tr>
<tr>
<td>Surface Contact</td>
<td>4</td>
<td>CONTA174</td>
<td>Full Model except Cryostat Bearing in certain cases</td>
</tr>
<tr>
<td>Surface Target</td>
<td>4</td>
<td>TARGE170</td>
<td>Full Model except Cryostat Bearing in certain cases</td>
</tr>
</tbody>
</table>

### 3.1.3. Contact definition and Geometry naming in Workbench

Individual sections were connected in individual Mechanical model. Final assembly of Top lid, Upper Cylinder, Lower Cylinder, Base section lugs, bearings etc. was done in one Mechanical model FIG. 4.

![Contact definition of Complete Cryostat model with bellows](image-url)
3.1.4. Cryostat bellows

Cryostat Bellows three dimensional stiffness was added to the model and these are defined with bushing option FIG. 5 in Ansys Workbench [7].

3.1.5. Contact formulation for Cryostat bearing and Male & Female Lugs

Formulation of Cryostat Bearing (Non-linear model) as it has sliding and rotating elements and Male and female Lugs (Non-linear Model) were defined as follows.

- Frictional Contacts Cryostat Bearing (Non-linear Model): Frictional contacts were defined between spherical and plane surface of Cryostat bearing along with no separation contact FIG. 6.
- Frictional contact were defined plane surface of Male and female Lugs (Non-linear Model) FIG. 6.

FIG. 5. Three Dimensional Cryostat bellow modelling

FIG. 6. Cryostat bearing and Male & Female Toroidal Lugs frictional contact definition and modeling
3.1.6. Cryostat Bearing (Linear Model)

Using Frictional contacts for the sliding Elements, lead to a non-linear solution. Cryostat bearing linear model is captured by combination of spring and Dashpot in parallel (Bonc-Wen model) [7]. The effective stiffness $K$ (N/mm) and effective damping $C$ (Ns) for bearing calculated as described in Bonc-Wen model using linear Equivalent Model in place of frictional contacts[7]. Various cases were considered for the calculation of $K$ & $C$ and respected values were input in Ansys via Bushing command. The results obtained from Cryostat bearing Frictional Contacts formulation and Cryostat bearing Equivalent $K$ and $C$ model and previous references [1, 2] are in close approximation.

![E.g. K & C values for Cryostat Bearing Max. Movement 12 mm](image)

**FIG. 7. Cryostat Bearing (Liner Model) K & C Values and application in Ansys**

3.1.7. Assembly of Subsection into Full Cryostat Model

Fig shows fully meshed and assembled Cryostat Model.

![Cryostat full meshed model](image)

**FIG. 8. Cryostat full meshed model**

4. LOAD APPLICATION AND RESULTS DISCUSSION

The developed FE model of Cryostat manufacturing model was assessed for Category-II loading and load case combination [3, 4, 5] i.e. Dead Weight + External Pressure + SL-1. Loads were applied respectively and the maximum total displacement is at cryostat basement i.e. 32.05mm. The maximum Von Mises Stress is 206MPa. Fine assessment is also done at critical locations by linearizing the FE model results to calculate membrane and bending stress [9]. The membrane stress, bending stress and membrane plus bending stress obtained by linearization are 147MPa, 114MPa, 151MPa respectively which is well within the defined limits. The first mode shape is observed at 5.5 Hz with spring-damper system equivalent model and first mode is at 8.6 Hz with bonded contact in seismic bearings TABLE 5. In both the model mass participation in first mode is nearly 90%. The Cryostat FE model was further assessed for Dead weight+ external pressure and Dead Weight + Internal Pressure 1.4 and Maximum vertical displacement values and stresses from these loadings are under allowable limits. Hence the developed FE model with unique approach of Cryostat manufacturing model is qualified.
Table 4. Structural Analysis Results

<table>
<thead>
<tr>
<th>Assessed failure modes:</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead Weight + External Pressure + SL-1</td>
<td><img src="image1.png" alt="Image" /> Total Deformation (mm): 32.05 <img src="image2.png" alt="Image" /> Von Mises Stress (MPa): 206.03</td>
</tr>
</tbody>
</table>

Table 5. Modal Analysis Results

<table>
<thead>
<tr>
<th>Mode</th>
<th>Equivalent spring-damper linear model</th>
<th>Non-linear Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y Direction Mode -1</td>
<td><img src="image3.png" alt="Image" /> Freq.: 5.50 Hz</td>
<td><img src="image4.png" alt="Image" /> Freq.: 8.69 Hz</td>
</tr>
</tbody>
</table>

5. DISCUSSION AND CONCLUSION

Cryostat FE model has been successfully developed with unique approach and validated for various load cases. The non-linearity (Cryostat Bearing) in the system has been addressed to linear system with equivalent linear model (spring & damper approach) which yields more or less accurate results and time required to converge the model reduced drastically. For design of complex Fusion reactor (Tokamak) component like Cryostat by ASME Sec VIII Div. 2 (Design by Analysis), FE model development is an important aspect. The paper presents a unique Finite element Method for developing FE model of complex systems. This method can be adopted for FE modelling of other major complex fusion systems in future.

REFERENCES

[9] ASME Boiler and Pressure vessel Code Section VIII Div. 2 (Design by Analysis)