Abstract - The SST-1 is a steady state super conducting tokamak, which is in the final phase of commissioning tests. It has a major radius of 1.1 m with plasma minor radius of 0.2 m, with maximum toroidal magnetic field of 3 Tesla at the plasma center. The mission of the SST-1 project is to address physics and engineering issues related to steady state tokamak operation. The super conducting magnet system of SST-1 comprises of Toroidal field (TF) and Poloidal field (PF) coils. The 16 TF coils are nosed and clamped towards the in-board side and are supported toroidally with inter-coil structure at the out-board side, forming a rigid body system. The 9 PF coils are clamped on the TF coils structure. The integrated system of TF coils & PF coils forms the cold mass of @ 50 Ton weight. This cold mass is accommodated inside the cryostat and freely supported on the 16 cantilevers welded to the toroidal rigid support ring at 16 locations and support ring in-turn supported on 8 columns of machine support structure. During the operation this cold mass attains a cryogenic temperature of 4.2K in the hostile environment of high vacuum $1 \times 10^{-5}$ mbar. The thermal excursion of cold mass and its supporting structure during this cool down results into severe frictional forces at the supporting surfaces. In this paper, we discuss the effect of coefficient of friction ($\mu$) on von-Mises stresses in cold mass support structure of SST-1 machine and need for lubrication, by performing non-linear (contact) structural analysis, using Finite Element Analysis code ANSYS. We estimate the maximum stresses in the structure for various coefficients of friction and compare them with analytical values. Analysis results show that there is a design requirement of introducing a thin layer of solid lubricant film of MoS$_2$, having co-efficient of friction 0.05 between the sliding surfaces to control the stress contribution due to the friction.

I. INTRODUCTION

SST-1\(^{(1)}\) is designed for plasma discharge duration of 1000 seconds and configured to run double null triangular elongated plasma. SST-1 is presently in the phase of commissioning tests at Institute for plasma research, India. The SST-1 tokamak comprises of the machine support system, magnet system, vacuum system, the plasma facing components, and other auxiliary systems. An isometric cut-view of SST-1, indicating various systems is shown in Fig. 1. The cold mass support structure (CMS), a critical part of SST-1 support structure, supports 16 TF coil and 9 PF coils along with their corresponding support structures. Whole superconducting coil assembly is supported vertically on sixteen cantilevers welded to a support ring made in two halves with bolted joint having 3760 mm mean diameter with 140 square x 80 square hollow cross section. The support ring is freely sitting on eight brackets, which are welded to eight columns having 960 mm length, 168 mm outside diameter and 131 mm inside diameter.

Figure 1. Isometric cut-view of SST-1

The bottom of each column is again welded to eight circular flanges, which are bolted to the corresponding eight circular flanges welded to main support columns, which are in turn grouted to the machine foundation as shown in Fig.2. There are no mechanical joints between the ring and brackets as well as cantilevers and superconducting coils assembly. During cool-down, the cold mass structure attains a very low temperature of 4.2K from 300K. There are frictional forces between the ring and brackets and also between the sixteen cantilevers and superconducting magnet assembly. In the cool-down phase, the temperature in the column will have linear variation such as, 300K at bottom, 80K at thermal intercept, which is 150mm away from the bottom and 80K to 4.2K on the rest of the length.
II. MODELLING ISSUES

Taking advantage of the mirror symmetry in CMS geometry and loading, only 1/4th of the CMS has been modeled in ANSYS. The sixteen TF coils along with nine PF coils are sitting on sixteen cantilevers. The TF coils along with PF coils loading are simulated using blocks to apply the loads of superconducting magnets. The cylindrical co-ordinate system is used for the analysis. The solid model is having 23 volumes, 434 areas, 1182 lines and 786 key points. The 1/4th of the solid model is shown in Fig.3. The element used for meshing the solid model is a 20-node brick element SOLID 95. This element has three degrees of freedom (DOF), UX, U Y, U Z. The sliding with friction has been modeled using 3D contact-target element pair. The contact element is CONTA74 and the target is TARGE170. Eight contact pairs have been created, in which five are in between cantilevers & magnet blocks and the rest between ring & brackets. In meshing, both hexahedron and tetrahedron combinations are used. The finite element model is shown in Fig.4. The finite element model consists of total 87997 elements, in which 86442 are SOLID95 and 1555 are contact elements. The total nodal points are 169182, out of which 4463 nodes are associated with contact elements.

III. MATERIAL PROPERTIES

The material of CMS is 316LN. Since the structure has a wide temperature range of operation from 300K to 4.2K, the material properties like Young’s modulus and coefficient of linear expansion have been used with temperature dependent variation. Young’s modulus varies from 200.7 to 162.2 Gpa and coefficient of linear expansion varies from 10.5x10⁻⁶ to 15.65x10⁻⁶/K. The variation of Poisson’s ratio (ν) with temperature is negligible. The yield stress of material is 205Mpa, Ultimate tensile strength (UTS) is 515 Mpa and density considered for analysis is 7800 kg/m³.

IV. LOADS AND BOUNDARY CONDITIONS

Two types of loads are acting on the CMS. The structural loads and the Body loads (temperature loads). The structural loads include the weight of the superconducting magnets, 490.5 kN, and self-weight of the CMS, 31.197 kN. The weight of the magnets is applied on magnet blocks by converting into equivalent pressure of 0.4866 Mpa. The self-weight of structure is applied by defining density and acceleration due to gravity, 9.81 m/sec². The Body loads at different locations are applied as temperature. During the operation except the columns, rest of the components is at 4.2K. In columns the temperature gradient as discussed earlier is applied along the Z direction (height). The two regions are identified, 80K to 4.2 K and 300K to 80 K. The reference temperature is taken as 300K. Boundary conditions are properly defined as per the CMS designed. The bottom of the flange is constrained in vertical direction, Uz=0. On bolting holes of the flange, all degree of freedom is defined as zero. Toroidal movement of the magnet block is constrained, Uθ=0. To simulate the donut effect of the magnet assembly, nodes on magnet block are coupled for vertical and radial deflections. Also symmetric boundary conditions on two ends of the model are applied.

V. ANALYSIS STRATEGY AND ASSUMPTIONS

The operating conditions are such that initially, the whole CMS is at room temperature, 300K and is loaded with magnets. Now the structure is cooled down to 4.2 K with temperature gradient in the columns. Based on the operating conditions, the body load cases as defined in Table: 1 are considered to study the effect of each case on stresses developed in CMS. The load case represents the actual operating conditions of CMS. The above strategy is followed for μ (coefficient of friction)=0.10 & 0.25, to study the contribution of each load case on the resultant stress. Analysis with load case: 3(FBL case) is carried out for μ = 0.05 & 0.85 in addition to 0.25 & 0.10. It is assumed that all the welded joints, between the cantilevers and ring, brackets and columns, columns and flanges are 100% efficient. Also the bolted joints in the ring are 100% efficient.

VI. ANALYSIS RESULTS

The stresses (von-Mises criterion) obtained from FEA code, ANSYS for FBL condition are shown in Table: 2. The maximum stress is found to be at the foot of the column for all the values of μ (coefficient of friction). The stresses are found to increase with increase in μ. The von-Mises stress distributions for μ=0.05 and μ=0.85 are shown in Fig.5 and Fig.6 respectively. The von-Mises stress varies linearly with μ. The maximum stress in FBL condition for various μ is found to be on outer side of the foot of the column. The column deflects radially inward and the deflection is higher for higher μ because of larger frictional force acting on that.
When the temperature of CMS goes from 300K to 4.2K, the ring contracts and slides towards the center.

<table>
<thead>
<tr>
<th>Load case</th>
<th>Body load</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Case:1</strong> (No Body Load) NBL</td>
<td>Whole system is at 300K and no body load</td>
<td>The resulting stresses due to structural loads only</td>
</tr>
<tr>
<td><strong>Case:2</strong> (Partial body Load) PBL</td>
<td>The reference temperature is 300K. The ring is made to contract by applying temperature on all the components of CMS except the columns that are at uniform temperature of 300K.</td>
<td>The resulting stresses due to structural loads combined with stresses due to frictional force originated due to the sliding of ring on the bracket</td>
</tr>
<tr>
<td><strong>Case:3</strong> (Full Body Load) FBL</td>
<td>The reference temperature is 300K. Except the column rest of the components of CMS are at 4.2K. There is a temperature gradient in the column as mentioned in body loads</td>
<td>The resulting combined stresses are due to load case: 1 and load case: 2 and due to the temperature gradient in the column.</td>
</tr>
<tr>
<td><strong>Case:4</strong> (Only column with thermal gradient)</td>
<td>The reference temperature is 300K. Temperature gradient in the column as mentioned in body loads is applied. Flange is at 300K</td>
<td>The resulting stresses due to temperature gradient only. For any value of µ, the stresses at component levels should match with those obtained by subtracting from FBL to PBL.</td>
</tr>
</tbody>
</table>

When the ring is sliding, the bottom surface is subjected to frictional force, but the top surface is free from the frictional force. This results to shearing of the ring towards the center and causing twisting. The twisting of the ring is higher for higher values of µ as shown in Fig.9 &10. Since the ring has larger twisting for higher values of µ, the cantilever welded to ring has more deflection for higher values of µ as shown in Fig.7. The coefficient of friction (µₐ) has been calculated from reaction forces on column obtained from FEA results and compared with the input values of µ as shown in Table: 3. It is also observed that the stresses in the ring for various µ are in the range of 70-80 Mpa and maximum stress is at the junction of ring and cantilever. The maximum stress in the ring is less than that in the column. The maximum stress (von-Mises) in the column is found to be 105Mpa and is independent of structural loads and loads due to friction.

The von-Mises stress in the column has been estimated analytically and compared with those obtained from ANSYS. In analytical calculations, the stress (σₓ) at component level is taken from case: 4 loading and in addition to this stress component, there is one more normal stress component, in the same direction from eccentric loading. This stress is estimated by using flexural stress theory [3] and this stress depends on friction force. The final stresses for various µ are calculated by von-Mises criterion. The comparison of von-Mises stresses calculated analytically and obtained from FEA and contribution of stresses due to frictional forces is studied.

<table>
<thead>
<tr>
<th>Coefficient of friction (µ)</th>
<th>Maximum stress in Mpa (von-Mises)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>118</td>
</tr>
<tr>
<td>0.10</td>
<td>126</td>
</tr>
<tr>
<td>0.25</td>
<td>158</td>
</tr>
<tr>
<td>0.85</td>
<td>276</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Input values in FEA (µ)</th>
<th>Horizontal reaction force in column Rₓ N</th>
<th>Vertical reaction force in column Rᵧ kN</th>
<th>Coefficient of friction calculated from Rₓ and Rᵧ (µₐ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>2660.2</td>
<td>64.986</td>
<td>0.040</td>
</tr>
<tr>
<td>0.10</td>
<td>5831.6</td>
<td>64.987</td>
<td>0.089</td>
</tr>
<tr>
<td>0.25</td>
<td>15331</td>
<td>64.972</td>
<td>0.235</td>
</tr>
<tr>
<td>0.85</td>
<td>53072</td>
<td>64.864</td>
<td>0.818</td>
</tr>
</tbody>
</table>

When the temperature of CMS goes from 300K to 4.2K, the ring contracts and slides towards the center. **Table: 1 Load Cases**

**VII. CONCLUSIONS**

We understand from the FBL analysis case with µ=0.05 that the maximum von-Mises stress is 118Mpa and the location is outer side of the foot of the column as shown in Fig.11. In
load case: 4, the maximum von-Mises stress is 105 Mpa and this stress is independent of coefficient of friction. Even when the sliding surfaces of the structure are made free from friction i.e. \( \mu = 0 \), the von-Mises stress in the column will have a minimum value of 105 Mpa, if stress contribution from eccentric loading is neglected. If \( \mu \) is high, the contribution of stresses due to friction will increase, for example, when \( \mu = 0.85 \), the maximum von-Mises stress is found to be 276 Mpa. In this case, the contribution of stress due to friction at component level is 179 Mpa. It is also clear from the Fig. 8 that the structure reaches the yield stress, 205 Mpa, if \( \mu = 0.489 \). So in order to control the stress contribution due to friction, the sliding surfaces should be lubricated to provide a \( \mu = 0.05 \). Improving \( \mu \) beyond 0.05 (corresponding von-Mises stress is 118 Mpa) will not help much in reducing the stresses because it is found that with \( \mu = 0 \), the von-Mises stress is 105 Mpa which is close to the one when \( \mu = 0.05 \).

It is also mentioned earlier that this system would be operated in high vacuum environment, the candidate material for lubricant has to be high vacuum compatible and the suitable material is molybdenum disulphide (MoS\(_2\))\(^{[2]}\). With MoS\(_2\) coating we can achieve a coefficient of friction around 0.05 and corresponding stress is 118 Mpa, which is well within permissible stress limit. The future work includes calculation of stresses when \( \mu \) is not same on all sliding surfaces. This case may arise if there would be a wear of MoS\(_2\) locally on sliding surfaces.

**REFERENCES**

