Structural Integrity of Rod Cluster Control Assembly of Chashma Nuclear Power Plant -1

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ABSTRACT

This study has been made in an attempt to verify the structural integrity of Rod Cluster Control Assembly (RCCA) of Chashma Nuclear Power Plant-1 (CHASNUPP-1) using ANSYS computer code. The CHASNUPP-1 (PWR type, 300 MWe capacity, First unit) was built by China at Chashma (District Mianwali), Pakistan. The plant is successfully operating since 2000. The rod cluster control assemblies (RCCA) are used to control fast reactivity changes in PWR type reactors during the normal operation and accident conditions. To fulfill this function the RCCA is stepped upwards or downwards by control rod drive mechanism (CRDM). The stepping action produces a large amount of acceleration. The load produced during stepping is normally considered as limiting one. In this work we have considered the experimental results of a test conducted in China. The test [1] was performed to measure the acceleration produced in upward and downward stepping by CRDM on RCCA, at room temperatures, both in air and static water. The test results showed acceleration (g, m/s²) values, 10.8 – 51.0 & 46.4 – 78.0, in air and static water environments, respectively. Making the analysis on conservative side we selected the highest value of acceleration, 78 g, for our study.

To ensure the structural strength, a finite element model of CHASNUPP-1 RCCA has been developed simulating the loading conditions prevailing during reactor operation. This model has been analyzed using the Finite Element Code. The Maximum Stress intensity obtained through this analysis, 186 MPa, is less than the yield stress of RCCA material (~SS 321), 205 MPa, thus fulfills its structural integrity criteria.

KEYWORDS: Structural integrity, Control rod drive mechanism, Rod cluster control assembly, Finite element model, Stress intensity, Yield stress.
1. INTRODUCTION

There are three means to control the excess reactivity in the pressurized water reactors. These are soluble boron, solid burnable poison and control rod. The rod cluster control assemblies (RCCAs) are used during the normal operation and accident conditions to control fast reactivity changes. A sufficient negative reactivity will be introduced into the core along with drop under gravity to prevent the reactor from returning back to criticality.

The RCCAs are connected with the flexible couplings of drive shaft assemblies for control of nuclear reactivity. The RCCA with drive shaft can be stepped upwards or downwards by driving of control rod drive mechanism (CRDM), so that RCCA can be stopped at any position of the core. Tripping (Scramming) is accomplished by simply de-energizing the mechanism and allowing the control rods to fall by gravity into the core.

The RCCA and Spider Assembly, a key subassembly of RCCA, are shown in Figs. 1 and 2, respectively. The Spider Assembly is in the form of a control hub with radial vanes containing cylindrical fingers from which the absorber rods are suspended.

The functional requirements of spider assembly include:

- Allow connection with the control rods to form a RCCA.
- Allow connection to the drive shaft assembly.
- Can bear up impact loads of the CRDM stepping and rods drop.
- Can absorb remaining impact energy of the RCCA trip end.

During the reactor operation several kinds of loads act on RCCA and its Spider Subassembly, such as:

- Stepping force of CRDM.
- Impact force caused by dropping of RCCA during reactor trip.
- Hydraulic force.

However, the force experienced during the stepping by CRDM is considered as the limiting load for spider. In this work we have considered the experimental results of a test conducted in China. The test [1] was performed to measure the acceleration on RCCA, produced in its upward and downward stepping by CRDM, at room temperatures, both for air and static water. The test results showed acceleration (g, m/s²) values, 10.8 – 51.0 & 46.4 – 78.0, in air and static water environments, respectively. Making the analysis on conservative side we selected the highest value of acceleration, 78 g, for our study.

In order to ensure the reliability and safety of RCCA of CHASNUPP-1 reactor, it is essential to perform the finite element stress analysis of its key subassembly i.e. Spider Assembly for stepping load i.e. 78g. In this regard, a finite element model of CHASNUPP-1 RCCA has been developed and analyzed using Finite Element Code ANSYS 10. An attempt has been made to simulate the loading conditions which prevail during reactor operation.
2. FINITE ELEMENT MODEL

The RCCA of CHASNUPP-1 fuel is symmetric about both axes in the cross-section. The symmetry boundary conditions are true in respect of geometry, loads and constraints, and for material properties. Therefore, in this analysis advantage of symmetry has been taken into account by considering only 1/8th part of RCCA to reduce the size and computational time of the model. All dimensions of the geometric model are according to the drawings of CHASNUPP-1 RCCA.

For the analysis of the model using ANSYS code, first of all the area of the spider vane has been created and divided into regular areas for mapped meshing, using Boolean operations. The volume of the spider assembly has been created by extruding its area. After this step the volume has been divided by areas to convert into regular volumes required for mapped meshing.

The 3-D finite element model (FEM) has been generated by mapped meshing the volume using Solid 45 type elements.

Fig. 3 & Fig. 4 show model geometry and finite element model (mesh) in 3-D along with all applied boundary conditions, respectively. Table 1 & Table 2 list number of entities of the model and the properties of material (0Cr18Ni11Ti) used for fabrication of spider assembly for CHASNUPP-1, respectively. The said material is equivalent to AISI 321.

3. SIMULATION OF THE LOADING CONDITIONS

After developing the finite element model the next step is to apply carefully the loads and constraints representing the loading conditions.

3.1 Boundary condition

The control rod drive mechanism of RCCA is attached to the spider, through flexible coupling of drive shaft assembly, inserted into the trapezoidal grooves at the top end of spider. As described earlier, the test shows 78g as the maximum load, which is equivalent to multiple of 78 times the weight of 20 control rods. This load is distributed on 16 radial vanes of the Spider through 20 control rods attached to it [2].

3.2 Analysis method

The 3-D plot of the load environment to which the model has been subjected, as described above, is presented in Fig. 4. The model has been evaluated under linear static condition.

To simulate the symmetry boundary conditions, translations of all the nodes at inside edges for 1/8th portion of the plates are fixed. The nodes along the X-axis are fixed in Y-direction, whereas the nodes along the diagonal are rotated at 45° and are fixed in Y-direction.
To constraint the model, nodes associated with the top surface of spider nearer its grooves are fixed in X, Y and Z-directions. The load has been applied on areas around control rods, where they are suspended, screwed/welded by means of nuts with the spider vanes.

The total load applied is 31742.2 N (multiple of 79 times the weight of 20 control rods) has been distributed on twenty areas around the holes in spider vanes for control rods. Force around one control rod hole is distributed over respective number of nodes attached to its peripheral area.

Let, total load applied = $F_T$
Total number of control rod holes = $N_{CT}$
Force around per control rod hole = $F_{CT}$, then
$$F_{CT} = \frac{F_T}{N_{CT}}$$

Number of node at peripheral area = $N_N$
Load per node = $F_N$, then
$$F_N = \frac{F_{CT}}{N_N}$$

Force applied on node at symmetry edge is half of $F_N$.
The room temperature has been assumed for the analysis.

4. **ANALYSIS OF RESULTS**

The value of maximum tensile stress in X-direction (X-Stress) is found to be 91.31 MPa, located on area around the hole in the top surface of longest vane of spider, where the control rod is suspended. The minimum compressive stress in X-direction having value -129.28 Mpa, is located opposite to the max. stress position, i.e. on bottom surface of the same spider vane. X-stress plot of the spider is shown in Fig. 5.

In case of Y-Stress, maximum tensile stress, 77.14 MPa, and the minimum compressive stress, having value -110.82 MPa, are located at the same location, where maximum and minimum values of X-stress lie. Stress plot of Y-Stress is shown in Fig. 6.

Therefore, the maximum stress intensity lies on the lower surface of the same longest spider vane at which X and Y stresses are maximum and its value is 186.19 MPa. Minimum stress intensity, 0.52 MPa, lies around the hole of the lower surface of second longer spider vane. Plot of stress intensity is shown in Fig. 7.

In figures representing general analysis, MX and MN denote maximum and minimum values, respectively.

The Table 3 & Table 4 represent the values of direct stresses in X, Y & Z-directions and the values of stress intensity & equivalent stress, respectively.
5. CONCLUSION

To ensure the structural strength, a finite element model of CHASNUPP-1 RCCA has been developed simulating the loading conditions prevailing during reactor operation. This model has been analyzed using the Finite Element Code. Under the applied load (78g, taken from the test) the Maximum Stress intensity obtained through this analysis, 186 MPa, is less than the yield stress of RCCA material (~AISI 321), 205 MPa, thus fulfills its structural integrity criteria [3,4].

6. REFERENCES

Table 1: Details of the Finite Element Model

<table>
<thead>
<tr>
<th>Entity</th>
<th>Numbered Defined</th>
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<td>ELEMENT TYPE</td>
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<td>NODES</td>
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<tr>
<td>ELEMENTS</td>
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<td>LINES</td>
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<td>AREAS</td>
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<td>VOLUMES</td>
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Table 2: Material Properties For Stainless Steel 0Cr18Ni11Ti (AISI 321)

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<th>Property</th>
<th>Value</th>
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<tr>
<td>Yield Strength (MPa)</td>
<td>≥205 [5]</td>
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<tr>
<td>Modulus of Elasticity (MPa)</td>
<td>2 x 10^5</td>
</tr>
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<td>Poisson’s Ratio</td>
<td>0.3</td>
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<td>Tensile Strength (MPa)</td>
<td>≥515 [5]</td>
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</table>

Table 3: Direct Stresses (MPa)

<table>
<thead>
<tr>
<th></th>
<th>X</th>
<th>Y</th>
<th>Z</th>
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<tbody>
<tr>
<td>Minimum</td>
<td>-129.28</td>
<td>-110.83</td>
<td>-119.10</td>
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<td>Maximum</td>
<td>91.31</td>
<td>77.15</td>
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Table 4: Stress Intensity & Equivalent Stress (MPa)

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<th>Stress Intensity</th>
<th>Equivalent Stress</th>
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<tbody>
<tr>
<td>Minimum</td>
<td>0.52</td>
<td>0.46</td>
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<tr>
<td>Maximum</td>
<td>186.2</td>
<td>166.0</td>
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</tbody>
</table>
FIG. 1 ROD CLUSTER CONTROL ASSEMBLY

FIG. 2 SPIDER ASSEMBLY
FIG. 3 MODEL GEOMETRY

Chasnupp-1 Rod Cluster Control Assembly

FIG. 4 All Applied B.C.’s (Element Plot 3D)

Chasnupp-1 Rod Cluster Control Assembly
FIG. 5 Plot of X-Stress (Deformed)

FIG. 6 Plot of Y-Stress (Deformed)
NODAL SOLUTION
STEP = 1
SUB = 1
TIME = 1
 viewpoints=6
SINT (AVG) = 52295
SMY = 186.195

Chasnupp-1 Rod Cluster Control Assembly

FIG. 7 PLOT OF NODAL STRESS INTENSITY (DEFORMED)