OPTIMIZATION OF THE SUPPORTING ARRANGEMENTS OF HIGH FLUX RESEARCH REACTOR (HFRR) CONSIDERING STATIC AND SEISMIC LOAD

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ABSTRACT

The proposed High Flux Research Reactor (HFRR) is a pool type research reactor, which consists of a large structure called core-chimney over its core. The static and seismic load generates a high stress level in its components. Here, it was proposed to incorporate a flexible component (bellow) and sliding support for core-chimney to reduce the stress level. The sliding support for core-chimney is to reduce its response by dissipating energy into sliding. The system becomes nonlinear because of the presence of sliding support. The natural frequency of the core-chimney decreases when it is made sliding so the net response of the core-chimney depends upon the increase in the spectral value corresponding to the frequency of more flexible sliding core-chimney and the amount of energy dissipated into the sliding. The time history analysis can simulate the exact nonlinear behavior of the system for seismic load but for such a complex nonlinear system the analysis is very much time consuming and also very complex. Here, a procedure for linear analysis was also established which takes care of nonlinearity in the system. The procedure was also verified through the time history analysis. The analysis required the coefficient of friction of sliding surfaces (SS to SS) in water, which is not available in the literature so an experiment was carried out to find it.
It was observed that the energy dissipation in sliding was not enough to reduce the response of core-chimney and hence the load on the flexible component (bellow). As an alternate, It was proposed to incorporate Base Isolator. It reduces the relative motion among all components and hence the stress level.

INTRODUCTION

The proposed High Flux Research Reactor (HFRR) is a 30MW (thermal) pool type research reactor. The reactor core is located on a core grid plate supported from the pool bottom. The core is surrounded by an annular cylindrical tank filled with heavy water. The light water coolant flows from bottom to top across the core. A chimney is provided to collect the coolant at the core outlet and direct to the core outlet piping leading to the pump suction. The chimney is open at the top. It has one main pipe and two branches at 45 degree. The main pipe is connected to reactor core.

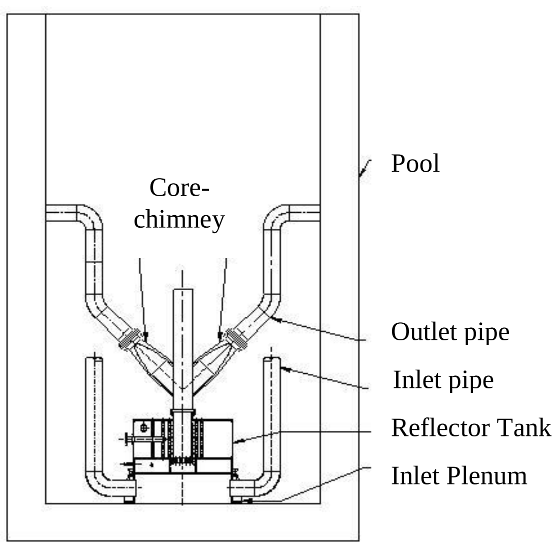


Fig.(1) – Schematic view of HFRR core-structure with pool.

The HFRR core structure was first analyzed for static loads only. It resulted into the incorporation of a support for the core-chimney and a flexible component called bellow between the Reflector tank and the core-chimney. The bellow was unable to take the seismic load so the support of chimney was made sliding to decrease its response and hence the load on bellow. The behavior of this system with sliding support is nonlinear when it is subjected to earthquake motion. The nonlinear time history analysis, which really simulates the nonlinearity, is not advisable for such a complex system because it takes a huge time and the analysis becomes so much complex. Earlier researchers have found that response spectrum method (linear analysis) can be utilized for piping supports on nonlinear supports using linearization technique. However the procedure is not fully established. And they had not tried for the submerged systems. Here the procedure for the appropriate linear analysis was first established and performed considering the energy dissipation due to sliding. The procedure is also verified through the nonlinear time history analysis. Here all the core components are submerged in water. The hydrodynamic effects have also been simulated by rigid and sloshing mass. The acceleration drag effect for each component has been taken care by its added mass.

FINITE ELEMENT MODEL

The HFRR core structures and pool were modeled mainly with shell and beam element. The fluid-structure interaction was modeled by rigid and sloshing mass using structural mass and spring element. The static loads are dead weight, pressure and temperature. The force developed because of change in the direction of flow of water was also considered. The FE model of core-structures is given in fig.2.a and fig.2.b. The FE model for the time history analysis was made simple by modeling the core structures only by beam element to decrease the no. of elements and the sliding interface was generated by the contact element.

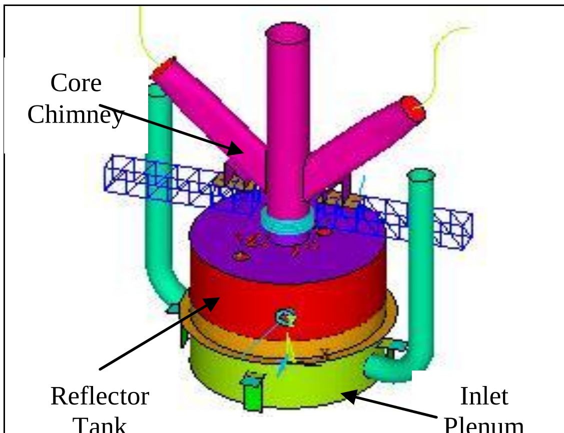


Fig. (2.a) - FE model of HFRR core structure (pool is not shown here).

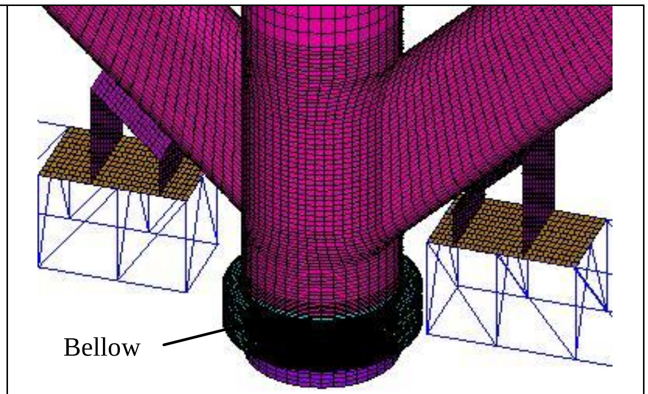


Fig. (2.b) - FE model of chimney with its support.

ANALYSIS

The static analysis was first performed. The core-chimney was first analyzed without its support. The outlet pipe where it goes inside the pool wall gets stressed up to 244 MPa as given in fig. (3). The branches of the core chimney are inclined so the horizontal movement of branched pipe also causes local stress of 140 MPa. at the point where it gets connected to the central pipe. The problem was solved by supporting the branches separately, which restricts the core-chimney in vertical and horizontal direction. The point of connection between the central pipe of core chimney and the Reflector Tank (made of aluminium) was stressed up to 126MPa because of the temperature load and the load on the top plate of the Reflector Tank due to internal pressure as given in fig. (4). The inclusion of bellow reduces such stress. But the bellow is not able to take the seismic load. The total stress of 222 MPa (157MPa due to seismic load and 65MPa due to static load) is developed in the bellow during seismic event as given in fig. (5). The permissible limit is 207MPa.

Analysis with Sliding Support

The support of the core-chimney was made sliding so as to decrease its response by dissipating the energy into sliding and hence by decreasing the displacement load on bellow. The core-chimney becomes more flexible when it is made sliding so the spectral value corresponding to its natural frequency increases but the sliding tends to decrease the response of the core-chimney by dissipating the energy. The net response of the chimney depends upon the amount of increase in the spectral value corresponding to decreased natural frequency of the chimney and the amount of energy dissipated into the sliding. The displacement load on the bellow was found to be 5mm and 5.1mm for the fixed and the sliding support, which implies that the sliding could only dissipate the extra energy of the core-chimney which was gained because of its more flexibility. There is no reduction in the stress level by introducing the sliding support.

The linear analysis was performed which takes care of the nonlinearity (sliding). The procedure for the linear analysis for such a system was first established which is explained later on. The analysis is called Iterative Response Spectrum (IRS) Analysis. The sliding distance of 4.75mm was observed through IRS, which was verified through the non-linear time history analysis as explained later. The bellow is over stressed. The incorporation of the base isolator results into the great reduction in the stress level of all components by decreasing the relative motion. The bellow now experiences the total stress of 44MPa only. The design of the base isolator has been discussed later.

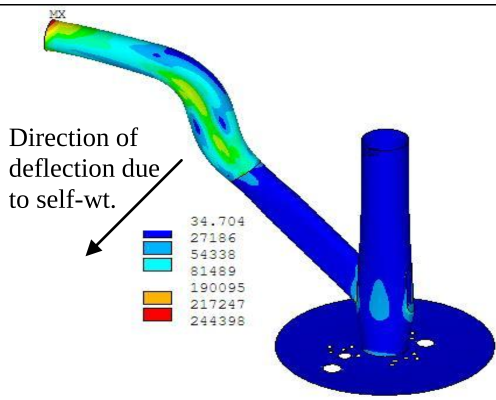


Fig. (3) – stress (10^{-3} MPa) in outlet pipe and core-chimney without its support

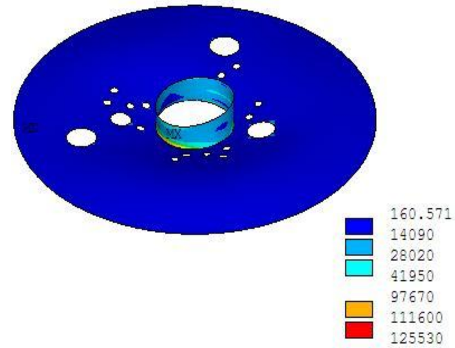


Fig. (4) – stress (10^{-3} MPa) in Top plate of Reflector Tank (for static load).

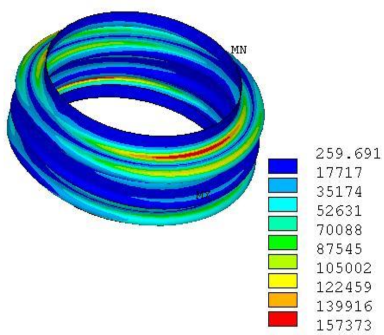


Fig. (5) – stress (10^{-3} MPa) in bellow (for seismic load).

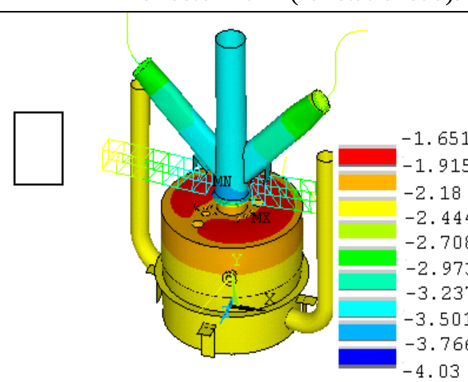


Fig. (6) – Vertical deflection (mm) with base isolator.

Iterative Response Spectrum Analysis (IRS) considering nonlinearity in friction support

The core–chimney, its support and pipes connected to the chimney has been well optimized such that the displacement response of the core-chimney near the support can provide sufficient damping by sliding. The modal analysis of the system shows that the frequency of the core chimney is 7Hz whose mode shapes show the proper sliding between core-chimney and its support in Z-direction. The response amplification for this mode is also sufficient to provide the enough inertia force, which is more than the limiting friction force.

The Response spectrum was performed using the structural damping alone and Z_1 was obtained. The inertia force experienced by the core-chimney is 4472N, which is more than the limiting friction force of 2762N so it is now confirmed that there will be sliding between the core-chimney and its support. Now, the equivalent damping was calculated for the mode based on the relative motion and the stiffness of the modes using the following equations.

$$\Delta E = 4FZ$$

$$\zeta = \frac{1}{4\pi}\left(\frac{\Delta E}{E_{SE}}\right) = \frac{2F}{\pi K Z}$$

$$E_{SE} = \frac{1}{2} K_Z Z^2$$

$$K_Z = 9 \times 10^6 \, Nm^{-1}$$

E_{SE} = Strain energy.
Z = displacement of chimney relative to its support.
ΔE = Energy dissipated in the friction.
F = Limiting friction force.
ζ = Damping ratio.
Kz = Modal stiffness for the mode having frequency 7Hz.
Now the response spectrum was performed again using the damping value equal to the damping of system and the damping due to sliding. The sliding distance was observed again. The damping was again calculated based on the displacement (Z_2) and the analysis was performed using this new damping. The procedure/iteration is continued till the two consecutive sliding distances should not vary with more than 1% of the previous value. The procedure is also explained in the (fig. 10). The final sliding distance calculated were confirmed by performing the time history analysis, which simulates the exact behavior of the system. The sliding distances and damping values at different iterations are given in the Table – 1. The stress value in bellow was found to be 157.4 MPa (fig.5) for the spectra having ZPA value of 0.2g as given in (fig-7).

Table –1. (Damping and sliding distances at different iterations for the mode having frequency 7Hz.)

No. of Iteration	ζ_Z Values			Sliding displacement		Lateral displacement load imposed on bellow
	ζ System	ζ Sliding	ζ Total	Value (mm.).	% Reduction	
1.	2%	0%	2%	7.5mm		
2.	2%	2.87%	4.87%	5.35mm	28.6%	5.75mm
3.	2%	4%	6%	4.93mm	7.85%	5.3mm
4.	2%	4.4%	6.4%	4.78mm	3%	5.1mm
5.	2%	**4.5%**	**6.5%**	**4.75mm**	**0.63%**	**5.08mm**

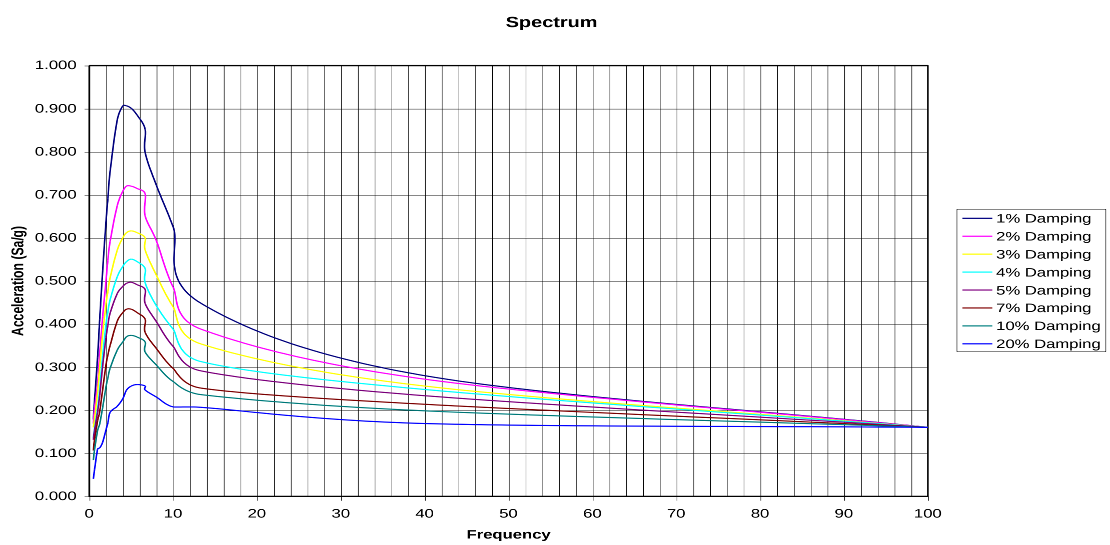


Fig. (7) – Tarapur spectra for different values of damping

TIME HISTORY ANALYSIS

The response of the core-chimney as observed through the established linear analysis was verified by the Time History Analysis, which simulates the actual behavior of the sliding interface. The FE model for the linear analysis consists of 40,000 elements so the time history analysis will be very much time taking and complex so the HFRR core structures was remodeled with beam elements (fig.8) only to reduce the number of elements and the complexities. The pool is modeled with shell element.

The time history analysis was performed using the value of kinetic friction coefficient equal to 0.26, which was obtained through an experiment inside water. The static coefficient of friction was found to be 0.3. The experiment set-up is shown in Fig. (11). A SS plate was hinged at one end and rotated from the other end very slowly by chain pulley to avoid the effect of inertia force. The static and the dynamic friction coefficient were obtained by the force balance equation. The sliding displacement obtained through the linear analysis matches with the result of time-history analysis (Table –1 and fig - 9).

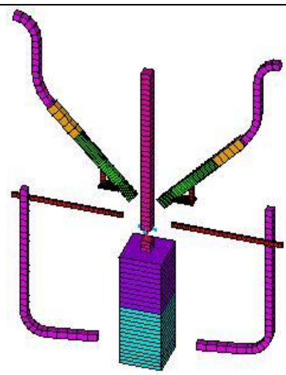


Fig. (8) – Beam model of HFRR for time history analysis

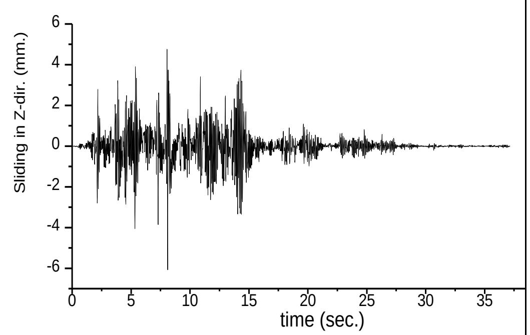
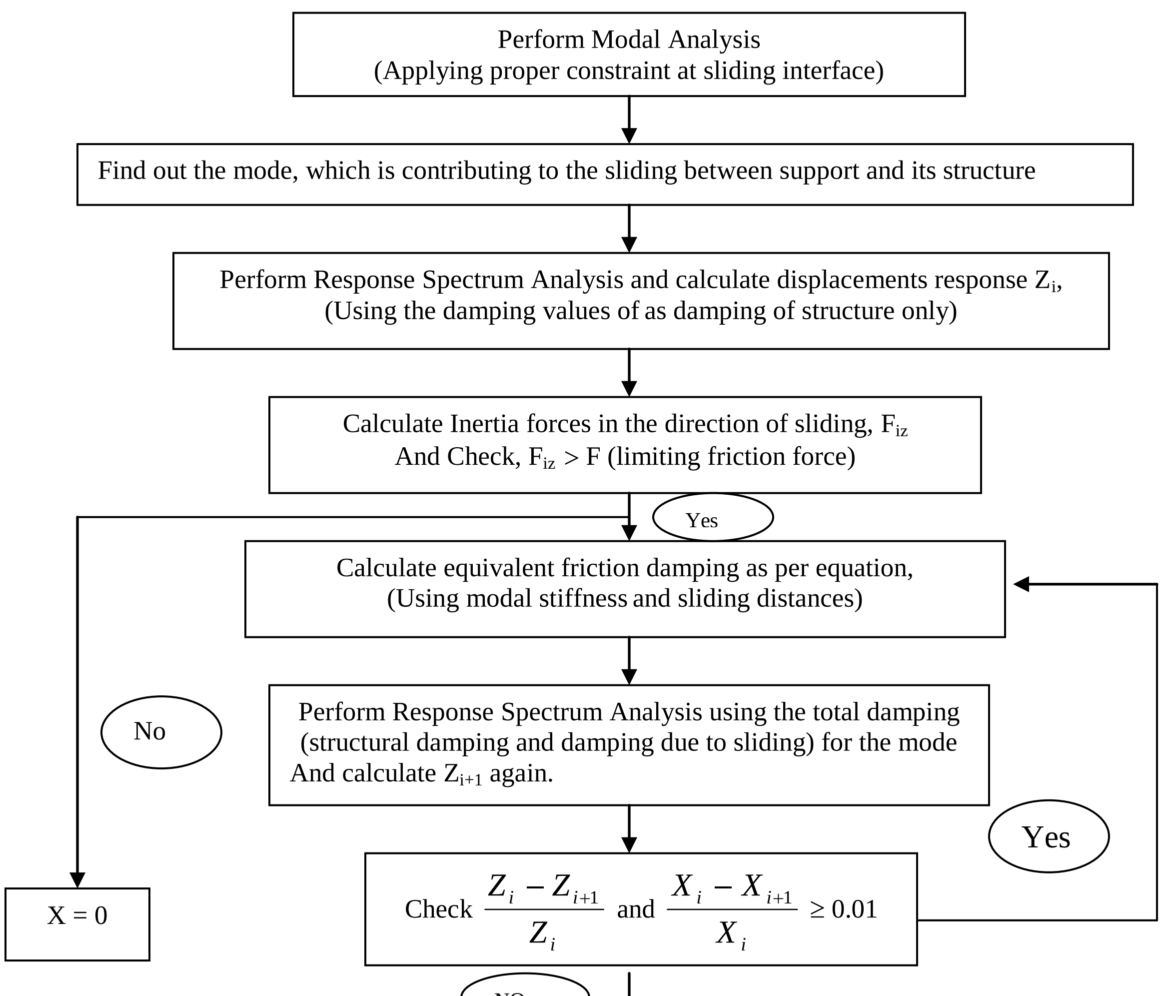


Fig.(9) – Sliding in horizontal Z-direction

Fig. (10) - Flow chart of the Iterative Response Spectrum method



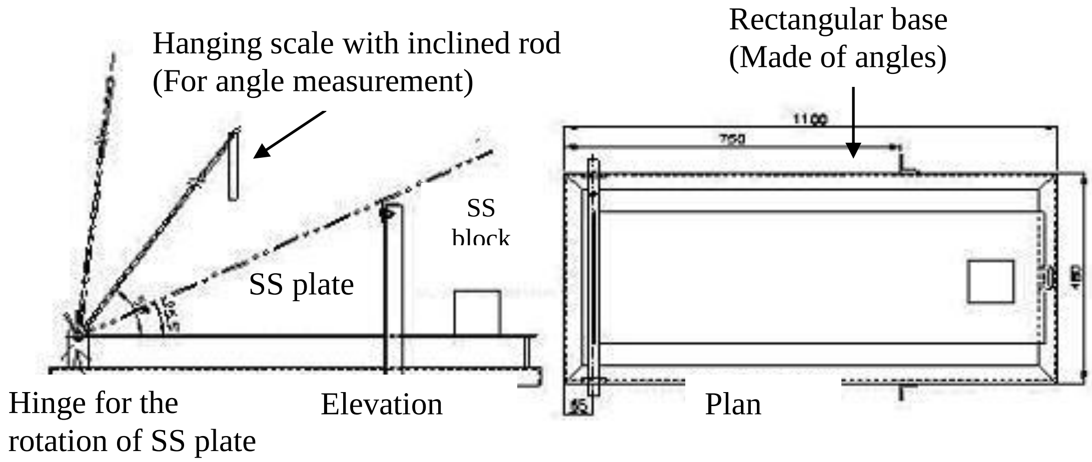


Fig. (11) - Friction experiment set-up.

BASE ISOLATOR FOR HFRR

The bellow is unable to take the seismic load. The bellow cannt be avoided as it was incorporated for static loads. The use of base isolator can be beneficial. Base isolatior is a mechanical component which substantially decouple a superstructure from its substructure resting on a shaking ground thus protecting a building or non-building structure's integrity. It is made flexible enough in the lateral direction so that the response with respect to that frequency becomes very less. Such flexibility is achieved by using rubber. The vertical stiffness can also be controlled by using steel plates between two rubber layers. The response can further be reduced if the base isolator is having damping. The rubber generally doesn't have damping but it can cause damping by making its force-deformation curve bilinear (fig.15) by incorporating the lead in the core of base isolator, which increases the area under the force-deformation curve. The area represents the loss of energy because of damping.

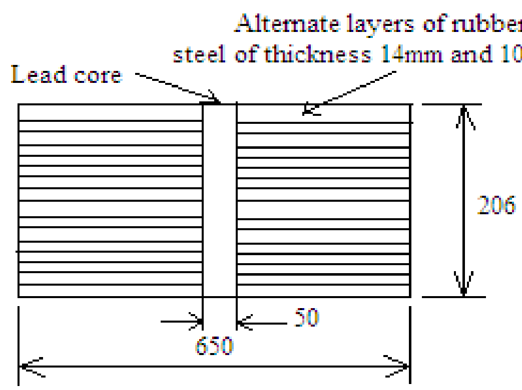


Fig. (12) – Dimensions of Base Isolator for HFRR.

FE modeling of Base Isolator

The base isolator for HFRR was modeled by three spring elements. The springs o-b and o-a as given in fig. (13) are in horizontal plane and provides the horizontal stiffness and the spring o-c provides the vertical stiffness. The stiffness of o-b and o-a is the linearized horizontal stiffness.

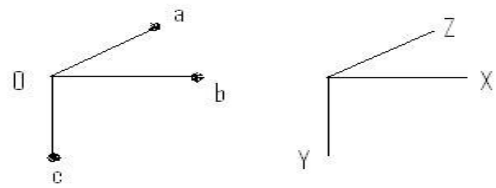


Fig. (13) – FE model of Base Isolator.

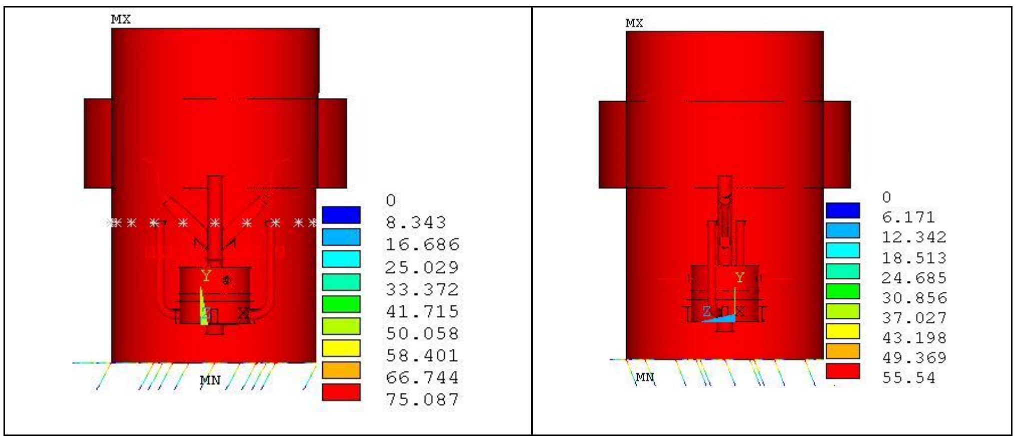


Fig. (14) – Deflection in X and Z horizontal direction (relative displacement among different component is almost 0.)

Here the base isolator has been designed for the horizontal frequency of 0.5Hz. The mode shape corresponding to the 0.5 Hz shows the rigid motion of the entire pool, which results into the negligible relative displacement of different core structures/components as given in fig.14. The force-deformation curve of this isolator is made bilinear (fig.15) by putting lead core, which results 9.1% damping. The lead core provides higher initial stiffness, which results very less deformation of BI for the other loads like, wind. The different parameters of this base isolator are given in table – 2.

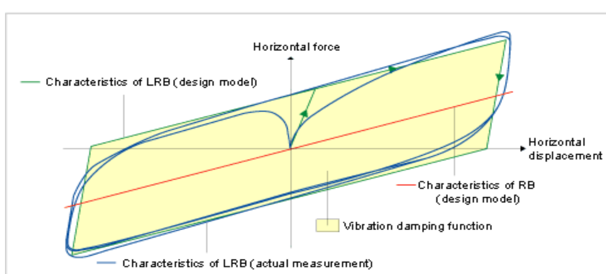


Fig.(15) – Force-displacement graph for the LRB

The base isolator normally supports a huge weight over it. It has comparable axial and lateral dimensions and a considerable amount of horizontal displacement is allowable. For a single type of loading on the bearing there are many factors get affected and one of those can cause failure. For example, the vertical load causes buckling and decrease in horizontal stiffness. The horizontal displacement can also cause buckling for vertical load, which is less than the critical load for buckling. The horizontal displacement can also cause decrease in horizontal stiffness.

Buckling Analysis – A multi layer elastomeric bearing can be susceptible to a buckling type of instability similar to that of an ordinary column but dominated by the low-shear stiffness of the bearing. The buckling load for the BI of HFRR is 1043 tones whereas the actual load on each BI is 154 tones only.

Critical Displacement – The buckling analysis for an elastomeric isolator is based on the linear theory analogous to the buckling analysis of a column and, as is the case in the usual theory, provides the buckling load in undisplaced position but no information on the stability of a bearing in the displaced position. The critical displacement is defined as the displacement under which the bearing exhibits zero incremental horizontal stiffness and the reduced area compression stress due to axial load reaches the critical load. The critical displacement here is 40cm. whereas the actual displacement is 7.5cm. only.

Rollout stability – In this case the bearing becomes unstable in the sense that beyond a certain displacement the force deformation curve has a decreasing slope. Because the bearing may not sustain tension, the movement at the top and bottom of the bearing is produced by change in the line of action of the resultant of the vertical load. The displacement for the rollout condition here is 21.4cm. whereas the actual displacement is 7.5cm. only.

Parameter	Values
Total no. of base isolator	21
No. of rubber layer in each isolator	9
Load on each BI	154 tones
Horizontal stiffness of each BI	1.244×10^{6}N.m^{-1}(0.5Hz)
Vertical stiffness of each BI	8.23×10^{8}N.m^{-1} (11.6Hz)
Damping	9.1%
Buckling load	1043tones (154tones in actual)
Vertical strain	1.5% (20% is the limit)
Critical Displacement	40cm. (7.5cm in actual)
Displacement for roll-out instability	21.4cm. (7.5cm in actual)

Table – 2. (Different parameters of BI for HFRR.)

CONCLUSION

The core-chimney becomes slight flexible when it is made sliding to dissipate energy. The increase in the flexibility tends to increase its response whereas the sliding tends to decrease its response. Here, in this case, the sliding could only release the energy, which was gained in extra because of its more flexibility so the stress level in the bellow (connecting reflector tank and the core-chimney) remains almost same which is more than the permissible limit. The incorporation of the base isolator makes the stress level well within the limits by decreasing the relative movement of different components/structures (fig.14).

The nonlinear analysis, which simulates the actual behavior of nonlinear system, takes much time and also the analysis becomes very complex so the procedure for the equivalent linear analysis was established. The procedure was also verified through the nonlinear time history analysis.

References

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