Decoupling Criteria with respect to Structural response of a Nuclear Power Plant Structure

Gundlapalli Prabhakar, U.S.P. Verma, A.S. Warudkar
Nuclear Power Corporation of India Limited, Mumbai, India.

ABSTRACT

An attempt has been made to study the structural response of calandria vault (CV) supporting the calandria endshield assembly (CEA) of pressurized heavy water reactor (PHWR). The entire structure has been considered as a multi-degree of freedom system with coupled and uncoupled CEA with CV. It has been found that the acceleration level at the point of coupling the subsystem varies with the two models studied. However, the response at the base of the structure does not alter significantly. The shear forces above and below the level of CEA are modified locally with the presence of coupled CEA, but the overall response does not alter. It has also been observed that the mass of the structure above the CEA also plays a major role in altering the overall structural response. In conclusion, the present study indicates, that, i) a detailed study for evaluating the de-coupling criteria of structures and equipment has to be established based on the mass distribution of the structure above and below the point where the secondary system is to be coupled or decoupled; and ii) revision of codal specifications to include the mass distribution in primary system and multi-point attachment of secondary system with the primary system

1. INTRODUCTION

The de-coupling criteria of structural systems is basically meant for two purposes, viz. a) for generating the floor response spectra to qualify the systems, equipment and components at various elevations and floors and b) for estimating the response of the structure for overall design. Different codes of practice indicate the criteria for de-coupling of structures, equipment based on a single spring-mass primary system, and another single spring-mass secondary system (SS) representing the equipment attached to the primary system (PS) as shown in Figure-(a). However, in the practical and real situation, the equipment is attached to more than one particular mass of primary multi-degree of freedom structural system as shown in Figure-(b).

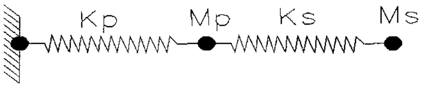

Figure (a)

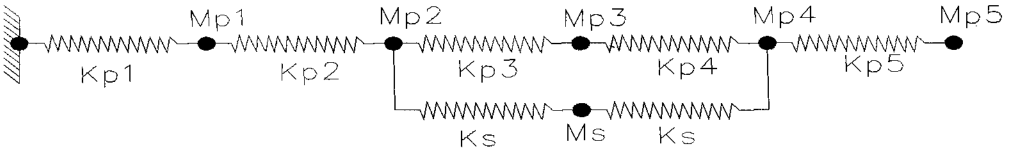

Figure (b)

Mp, Mp1 to Mp5 : Mass of primary system
Kp, Kp1 to Kp5 : Stiffness of primary system
Ms, Ks : Mass and stiffness of secondary system.

The additional masses present above and below the point, to which the secondary equipment is attached, play a significant role. These masses may decide whether the equipment is to be included or not for the purpose of estimating structural response for carrying detailed design of the primary structural system. To review these aspects, an attempt has been made to study the structural response of calandria vault (CV) supporting the calandria endshield assembly (CEA) of pressurized heavy water reactor (PHWR). The entire structure has been considered as a multi-degree of freedom system with coupled and uncoupled CEA with CV.

2. SECONDARY SYSTEMS WITH MULTI-POINT ATTACHMENT

The codal criteria based on the single point attachment of secondary system to the primary system can be represented as follows in figure (a). Further, if the SS is attached at more than one point, typically a SG to the internal structures or a CEA to the CV, this can be represented as follows in figure (b). Further, the 'Ms' can be attached to two or more points of primary structure as per the structural arrangement and system requirement. In such case, the analysis and design are going to be complicated, and the structural response may also depend on the mass before and after the point attachment of SS to the PS.

3. CODAL CRITERIA FOR DE-COUPLING OF SUBSYSTEMS

Different codes of practice, regulatory guides and applicable standards have criteria for de-coupling. These criteria are based on the mass ratio (R_m) and frequency ratio (R_f) of PS and SS. The codes are very specific to the single point attachment of SS to the PS, but do not deal with the SS having multi point attachment. A typical example being the USNRC NUREG-0800 [1] and ASCE: 4-86 [2]. In such cases, it is advisable to have a coupled model taking in to consideration the effects of mass and stiffness of both PS and SS. The USNRC defines the criteria for single point attachment based on the frequency ratio R_f and mass ratio R_m and states that, in general, the frequencies of system and subsystem have a negligible effect on the error due to de-coupling. However, the ratios are important to decide the decoupling of subsystem from the primary structure for the purpose of analysis and design of the primary structure and secondary systems.

Defining the R_m and R_f [1],

R_m	as the ratio of total mass of the supported subsystem to the total mass of the supporting system
R_f	as the ratio of fundamental frequency of the supported subsystem to the dominant frequency of the support motion,

Following three criteria are acceptable for decoupling of secondary structure from the primary structure:

i) If $R_m < 0.01$, de-coupling can be done for any R_f
ii) If $0.01 \leq R_m \leq 0.1$, de-coupling can be done if $0.8 \geq R_f \geq 1.25$
iii) If $R_m > 0.1$, a sub-system model should be included in the primary system model.

Further, if the subsystem is rigid compared to the supporting system and rigidly connected to the primary supporting system or PS, then, it is sufficient to include only the mass of subsystem at the supporting point of the PS. If the SS is supported by very flexible connection, then, the subsystem need not be included in the primary structure model. However, these criteria are qualitative and judgement of coupling or de-coupling is left to the structural analyst and designer. If R_m, R_f, or both are nearer to one of the above deciding criteria, it is always advisable to have a coupled analysis model to obtain a realistic response of PS and SS

The ASCE Standard [2] defines the mass ratio as the ratio of modal masses of the secondary system and primary system, and the frequency ratio as the ratio of uncoupled frequencies of the secondary and primary systems. Here, only the dominant modes, which contribute more than 20% of the total mass, must be considered for the calculation of these ratios. Hence, there can be a discrepancy to decide whether to couple or de-couple the subsystem under consideration. Further, the standard suggests that decoupling shall be avoided when the same results in significant errors, in case of subsystem supported at two or more points of the primary system. No general concurrence presently exists as to recommend the criteria. Hence this may lead to contraversy in applying the criteria for the design of the structure.

4. DESIGN PRACTICE

For the preliminary analysis and deciding the sizes of the members and sections of the structure, some approximation can be made for the SS and start with a de-coupled model analysis. Further, a refined and coupled analysis may be carried out to obtain a realistic response and reduce the uncertainties in the analysis and to estimate the margins available in the design. However, The floor response spectra (FRS) obtained from the uncoupled analysis is used for qualifying the sub-systems and components located on the floors. The final design with a further factor of safety leads to an over conservative design of systems or components. However, this may not be true in all the cases, as it is evident from the present study of calandria vault of a PHWR.

5. STRUCTURAL CONFIGURATION OF CALANDRIA VAULT

In the present study, the dynamic response of CV of PHWR is reviewed in brief. The typical Reactor Building (RB) of Indian PHWR consists of two containment structures. They are IC or primary containment made of PSC and OC or secondary containment made of RCC. In addition to these, there are structural walls, internal structures supporting a large number of equipment, systems and components. Major equipment being the CV, CEA, SG, PHT pumps, FM etc. Some of these equipment are not having mass comparable to the total mass of the RB. However, the CEA and SG are comparatively heavier and their contribution to the overall dynamic response of the RB and CV structure is significant.

The CEA consists of two end-shields of octagonal shape of a height about 9m with a calandria of cylindrical shape connecting the two end shields. The CV is rectangular concrete structure, and is 15.6m in the east-west direction and 8.36m in the north-south direction. The height of CV is 19.5m, from EL.96.0m to EL.115.5m. The CEA is housed in CV and is more or less rigidly connected in the EW direction within the octagonal openings of CV. However the CEA is flexible in the North-South NS direction and is connected to the walls of CV all around the opening by bolts, hence may experience small amount of translation during any seismic motion.

6. DESIGN OF CALANDRIA VAULT

The preliminary analysis and design is carried out with an uncoupled three-dimensional cantilever model of entire IC, OC, IS, CV of RB. The ZPA and FRS for various floors of RB are evaluated from this analysis, to qualify different sub-systems and components present on these floors. This led to very high forces and moments in the sub-systems. To maintain the force equilibrium and compatibility, the supports of these sub-systems on the PS are normally designed for these higher and amplified reactions. The final design forces using this concept led to large reinforcement steel. This is of the order of seven layers of high strength deformed bars of 36mm diameter, in both horizontal and vertical directions. This is in both inner and outer faces of the vault, giving 28 layers of steel in the cross section of the wall. Such high reinforcement may lead to poor constructability, honeycombing and other related problems with reduced durability of the structure. To overcome these difficulties, the design aspects are studied in detail. Salient points of the study with respect to the structural response of calandria vault structure are presented here.

7. MODELING FOR ANALYSIS

The CV is considered as a lumped mass cantilever model having horizontal and rotational degrees of freedom. A total of 12 nodes are considered for the CV, top node is at EL.115.5m. The base of CV is considered fixed for all the degrees of freedom at EL.92.5m. The total mass of CV without CEA is 750.178 T-sec^2/m and the mass of CEA is 133.435 T-.sec^2/m. Mass of CEA can be considered either lumped at its center of gravity location (105.5m) or distributed at several mass points over its entire height. The natural frequency of CV is estimated as 6.64hz and that of CEA is 7.5hz, details of this calculations, analysis and modeling are not presented here. Hence the R_f is 1.129 and R_m is 0.178; looking into these two values of R_m and R_f and following the codal criteria, coupled model has to considered for the detailed seismic response analysis of CV.

For the connection details of CEA with CV, out of the total height of 19.5m of CV, CEA occupies a height of about 9.0m, i.e. 46% of the height of CV. Hence the coupled model of the structure with single point attachment of SS to the PS as per the code may lead to erroneous results and overestimate the accelerations around the CEA. Hence this calls for a continuous, or, discrete and multi-point attachment of SS instead of a single point attachment.

Considering the fixity details as explained in the structural configuration, two different models can be employed for NS and EW directions separately. For EW direction, a de-coupled model with total mass of CEA considered along the height is acceptable. Presently, for NS direction, the following five mathematical models are considered. The mass and stiffness parameters considered for the analyses are presented in Table-1. Details of these models are shown in Figure-1 and explained below.

Model Case-1: This is an uncoupled model, in which the mass of CEA is distributed over five elevations, viz. 101.76m, 103.95m, 105.5m, 107.5m and 109.24m, central mass is at 105.5m.

Model Case-2: This is a coupled model, here the CEA is coupled with the CV and the mass of CEA is distributed at five points. The five masses are connected by a rigid link. This approximation is suitable since the CEA very rigid along it's longitudinal axis and can have rigid body translation and rotation. These masses are connected to the CV by means of five translation springs. The spring stiffness is estimated based on the mass and natural frequency of the subsystem, i.e., the CEA .

Model Case-3: This case is similar to case-2 except the rigid link connecting the five masses of CEA is not present, there by allowing independent translation or rotation, thus accounting any relative movement of the nodal masses of CEA locally.

Model Case-4: This model is uncoupled with the mass of SS is approximated as a single mass and attached at the center of gravity of CEA to the PS (CV structure) as a single point attachment.

Model Case-5: In this model, the entire CEA mass is attached to CV by means of a single translation spring at the CG level of CEA. This takes the mass and stiffness of CEA into effect, thus satisfying the codal criteria for coupling of sub-systems.

8. STRUCTURAL ANALYSIS

The ground motion considered at the base of the CV is the acceleration response spectra of a nuclear power plant for SSE with 7% damping and 0.2g as ZPA. The structure is analyzed for the seismic motion to estimate the shears and moments at different elevations. The results of the analysis, typically, the bending moments, cumulative shear forces, storey shears forces, and acceleration levels at various mass points are presented in Table-2 through 5, and Figures-2 through 5.

9. RESULTS AND DISCUSSION

Reviewing the response at the base and near the base, whether the SS is coupled or de-coupled, attached at single point or multiple points, the shear forces and bending moments are not varying largely. However, there is a variation in the distribution of shears along the height of the structure. These aspects are shown in Figure-3. This further suggests that a more realistic approach needs to be followed when considering the coupling or de-coupling of large equipment to the primary structure like calandria vault or reactor building etc.

For the model cases 1,2 and 3, the variation of structural response is gradual and smooth. However, as expected for the cases 4 and 5, there is a sudden change in the shear above and below the mass point at El.105.5m, where, the total mass of the CEA is lumped at a single point. This calls for a change in the reinforcement amount and pattern at this location. These two cases (4 and 5) are evolved as per the stipulations of codes with single mass attached at a single point. With these two types of models, there can be difficulty in designing the primary structure. The design will have large amount of reinforcement to take care of these forces, and will be highly conservative and uneconomical.

10. CONCLUSIONS

Based on the present study, the following conclusions are drawn.

a) The response of the primary structure does not alter significantly at the base with the coupled or uncoupled model. The variation of shear force along the height of the structure varies to some extent with the modeling.

b) It is more realistic and appropriate to consider the mass of CEA distributed over its entire height to obtain smooth and uniformly varying forces in the PS. These forces, when combined with the response from all other static load conditions to arrive at the final design shears and moments will be more realistic for the prototype

c) The criteria for de-coupling of subsystems with single point attachment needs to be applied with care when analyzing the subsystems connected to the primary structure at more than one location.

d) There is a need to carryout further research related to multi point attachment of SS to PS, to supplement the existing codal stipulations for design of nuclear structure.

REFERENCES

1. NUREG-0800, (Formerly NUREG-75/087), Standard Review Plan, U.S. Nuclear Regulatory Commission, Article 3.7.2: Seismic System Analysis, De-coupling Criteria of Structural Systems.
2. ASCE 4-86, ASCE Standard, Seismic Analysis of Safety Related Nuclear Structures and commentary on Standard for Seismic Analysis of Safety Related Nuclear Structures, September 1986, American Society of Civil Engineers, clause 3.1.7 and 3.4.4.

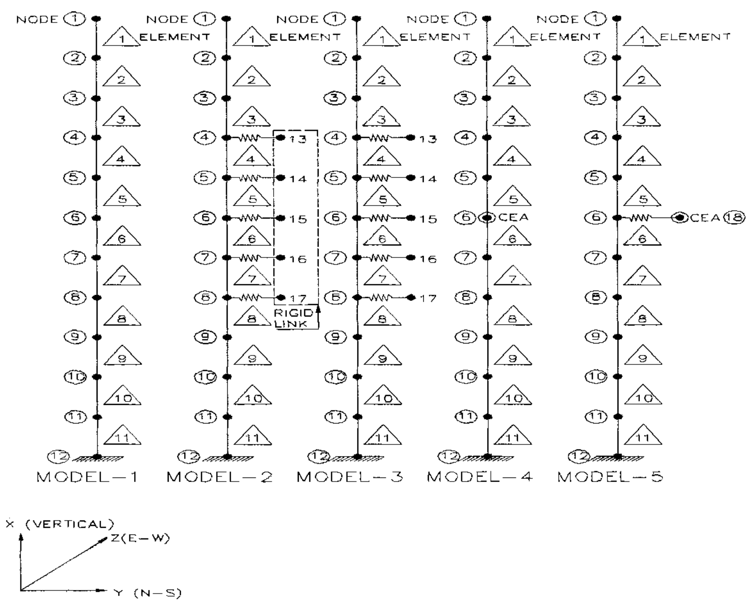

FIGURE-1 : FEM MODEL OF CALANDRIA VAULT AND END SHIELD ASSEMBLY

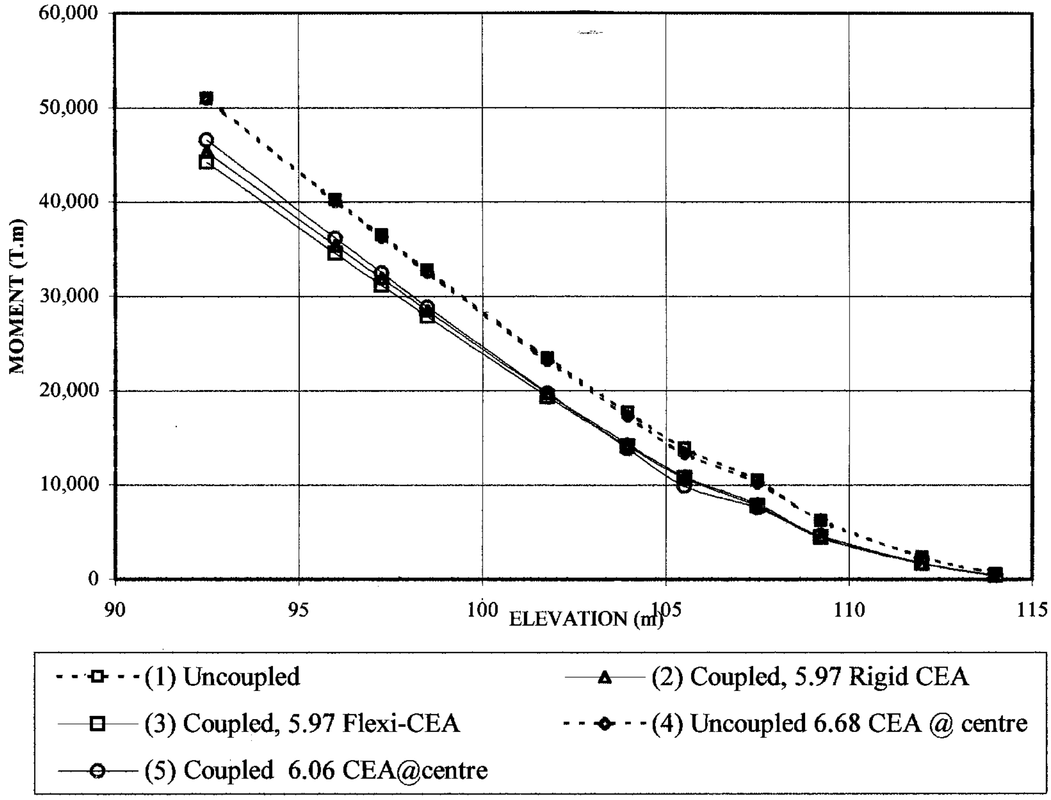

Figure-2: Variation of Moment

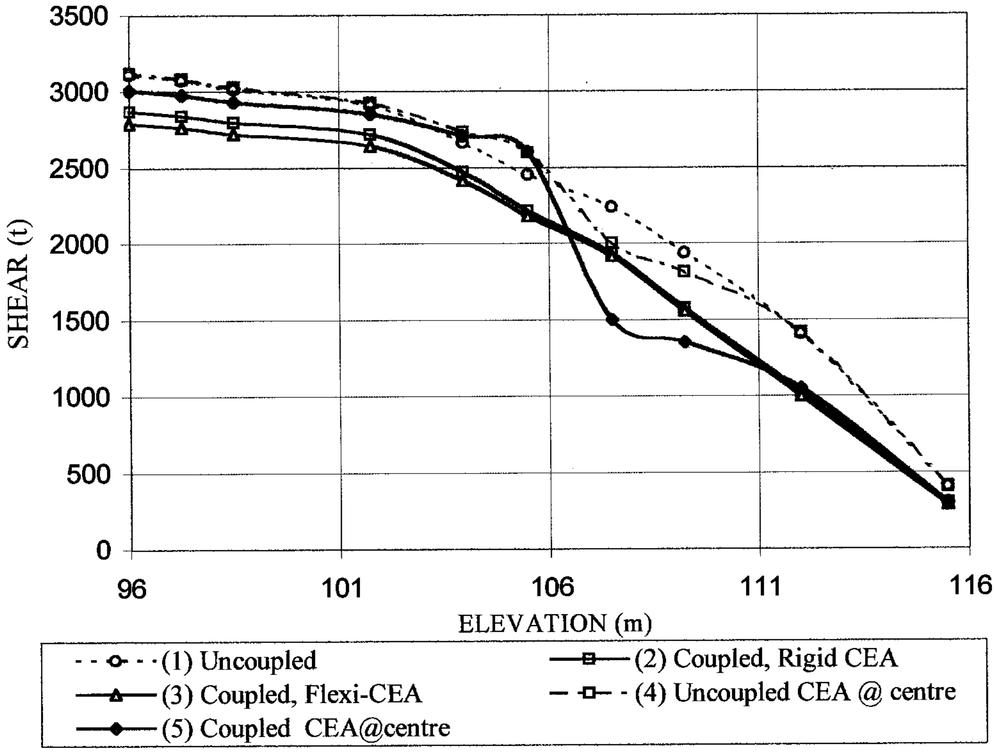

Figure-3: Variation of shear force

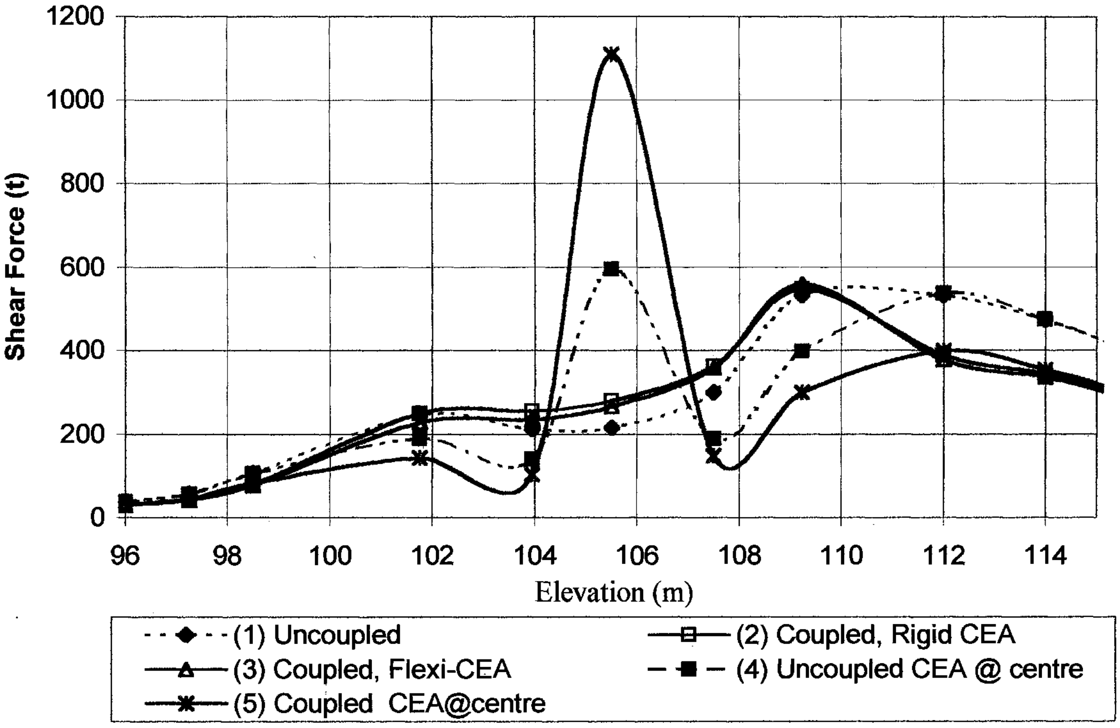

Figure-4: Storey Shear at various nodes

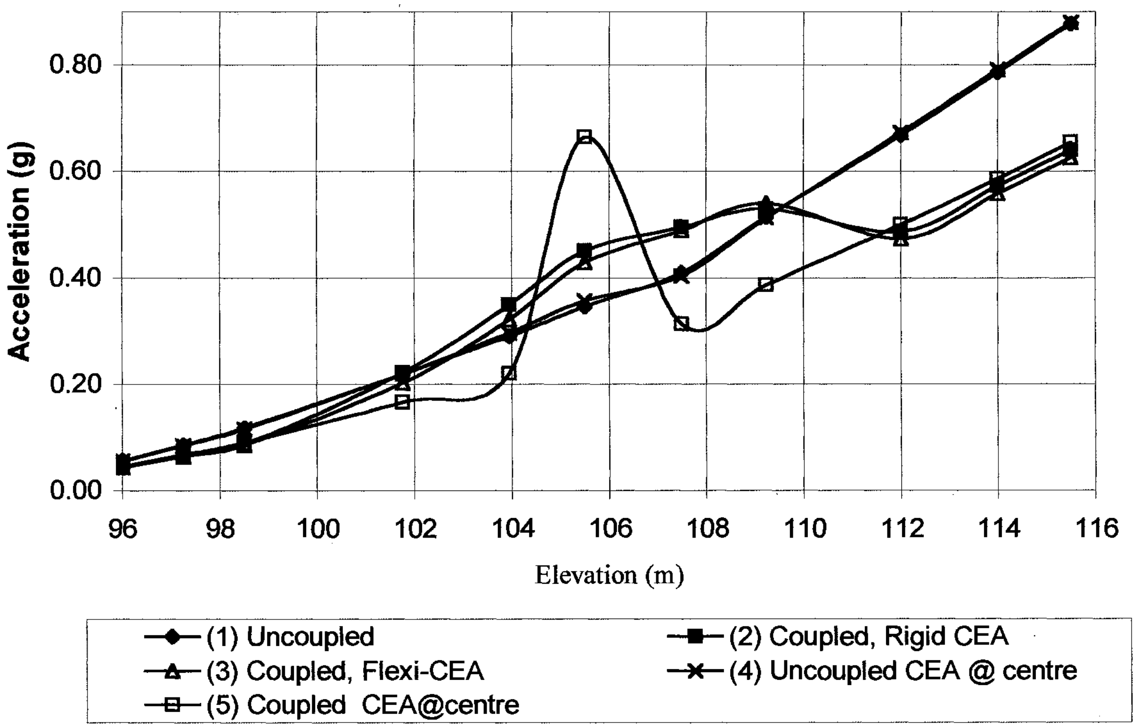

Figure-5: Acceleration at various mass points

Table-1: Axial area, Moment of Inertia and Nodal Mass								
		Mass at various nodes (T.sec.sec/m)						
Node	Elev. (m)	(1) Uncoupled	(2) Coupled, Rigid CEA	(3) Coupled, Flexi-CEA	(4) Uncoupled CEA @ centre	(5) Coupled CEA@centre	Axial Area (sq.m.)	Moment of Inertia (m4)
1	115.50	47.0	47.0	47.0	47.0	47.0	59.70	520.9
2	114.00	61.1	61.1	61.1	61.1	61.1	70.48	604.5
3	112.00	81.2	81.2	81.2	81.2	81.2	63.70	519.2
4	109.24	105.5	78.8	78.8	78.8	78.8	51.76	368.8
5	107.50	74.5	47.8	47.8	47.8	47.8	46.60	303.8
6	105.50	63.3	36.6	36.6	170.0	36.6	46.60	303.8
7	103.95	74.6	47.9	47.9	47.9	47.9	58.54	454.1
8	101.76	114.3	87.6	87.6	87.6	87.6	70.48	604.5
9	98.50	91.5	91.5	91.5	91.5	91.5	70.48	604.5
10	97.25	66.8	66.8	66.8	66.8	66.8	83.49	738.8
11	96.00	68.6	68.6	68.6	68.6	68.6	96.50	873.0
12*	92.50	35.2	35.2	35.2	35.2	35.2		
13	109.24	~~~	26.7	26.7	~~~	~~~		
14	107.50	~~~	26.7	26.7	~~~	~~~		
15	105.50	~~~	26.7	26.7	~~~	~~~		
16	103.95	~~~	26.7	26.7	~~~	~~~		
17	101.76	~~~	26.7	26.7	~~~	~~~		
18	105.50	~~~	~~~	~~~	~~~	133.4		

Nodes 4 to 8 are at the calandria level, central node is 6 at EL.105.5m

* Node-12 is with fixed boundary condition, hence mass at this node is not active

TABLE-2: Bending Moments in the structure						
		(T.m)				
Model Case		(1) Uncoupled	(2) Coupled,	(3) Coupled,	(4) Uncoupled	(5) Coupled
Nat.Freq.(hz)		6.64	5.97	5.97	6.68	6.06
Node	Elev. (m)		Rigid CEA	Flexi-CEA	CEA @ centre	CEA@centre
2	114.00	607	443	433	609	453
3	112.00	2359	1721	1680	2369	1761
4	109.24	6246	4554	4439	6280	4664
5	107.50	10465	7959	7807	10231	7602
6	105.50	13909	10922	10736	13320	9906
7	103.95	17673	14312	14071	17266	13841
8	101.76	23436	19658	19295	23165	19684
9	98.50	32771	28418	27806	32561	28873
10	97.25	36480	31873	31164	36292	32497
11	96.00	40255	35377	34569	40089	36173
12	92.50	50984	45308	44222	50892	46589

TABLE-3: Cumulative Shear in the structure						
		(1) Uncoupled	(2) Coupled,	(3) Coupled,	(4) Uncoupled	(5) Coupled
Model Case			Rigid CEA	Flexi-CEA	CEA @ centre	CEA@centre
Nat.Freq.(hz)		6.64	5.97	5.97	6.68	6.06
		3336.2	3203.0	3120.9	3324.5	3335.4
Node	Elev. (m)	Cumulative Shear (t)				
1	115.50	404.6	295.6	288.6	406.1	302.1
3	112.00	1407.6	1026.1	1000.0	1415.9	1051.6
4	109.24	1938.7	1574.0	1558.5	1812.5	1350.2
5	107.50	2237.8	1935.8	1915.8	2001.7	1496.9
6	105.50	2452.5	2215.3	2181.5	2596.3	2604.3
7	103.95	2664.7	2470.4	2416.6	2735.5	2707.7
8	101.76	2909.9	2718.7	2643.5	2923.4	2850.0
9	98.50	3015.8	2796.8	2719.7	3027.3	2931.3
10	97.25	3072.0	2839.1	2761.2	3082.2	2975.1
11	96.00	3110.4	2868.6	2790.2	3119.7	3005.5

TABLE-4: Storey Shear in the structure

		Storey Shear (t)				
Model Case		(1) Uncoupled	(2) Coupled,	(3) Coupled,	(4) Uncoupled	(5) Coupled
Node	Elev(m)		Rigid CEA	Flexi-CEA	CEA @ centre	CEA@centre
1	115.50	404.6	295.6	288.6	406.1	302.1
2	114.00	471.4	343.6	334.9	474.0	351.8
3	112.00	531.6	387.0	376.5	535.8	397.7
4	109.24	531.1	547.8	558.5	396.6	298.6
5	107.50	299.0	361.9	357.3	189.2	146.6
6	105.50	214.7	279.5	265.7	594.6	1107.5
7	103.95	212.2	255.1	235.1	139.2	103.3
8	101.76	245.2	248.3	226.9	187.9	142.3
9	98.50	105.9	78.0	76.2	103.9	81.3
10	97.25	56.2	42.4	41.5	54.9	43.8
11	96.00	38.4	29.4	29.0	37.4	30.4

TABLE-5: Accelaration at various mass points

		Accelaration (g)				
Model Case		(1) Uncoupled	(2) Coupled,	(3) Coupled,	(4) Uncoupled	(5) Coupled
Node	Elev. (m)		Rigid CEA	Flexi-CEA	CEA @ centre	CEA@centre
1	115.50	0.88	0.64	0.63	0.88	0.65
2	114.00	0.79	0.57	0.56	0.79	0.59
3	112.00	0.67	0.49	0.47	0.67	0.50
4	109.24	0.51	0.53	0.54	0.51	0.39
5	107.50	0.41	0.49	0.49	0.40	0.31
6	105.50	0.35	0.45	0.43	0.36	0.66
7	103.95	0.29	0.35	0.32	0.30	0.22
8	101.76	0.22	0.22	0.20	0.22	0.17
9	98.50	0.12	0.09	0.08	0.12	0.09
10	97.25	0.09	0.06	0.06	0.08	0.07
11	96.00	0.06	0.04	0.04	0.06	0.05

NOMENCLATURE

CEA:	Calandria Endshield Assembly
CV:	Calandria Vault
EW:	East -West
FM:	Fuelling Machines
FRS:	Floor Response Spectra
IC:	Inner Containment
IS:	Internal Structures
NS:	North- South
OC:	Outer Containment
PC:	Primary Containment
PHT:	Primary Heat Transfer
PHWR:	Pressurized Heavy Water Reactor
PS:	Primary Structure
PSC:	Pre-stressed Cement Concrete
RB:	Reactor Building (RB) of Indian
RCC:	Reinforced Cement Concrete
SC:	Secondary Containment
SG:	Steam Generators
ZPA:	Zero Period Acceleration