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Coupled fluid-structure interaction analysis of pressurised heavy water reactor calandria for sloshing and impulsive loads

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ABSTRACT

Pressurised Heavy Water Reactor calandria in horizontal configuration with multi- compartment shells poses many difficulties for qualifying it for hydrodynamic loads. A coupled 3 D shell - fluid model is studied in time domain with in house fluid-structure interaction analysis code FLUSHEL for this problem. The present paper also evolves a methodology to simplify the analysis procedure with due consideration to issues with regard to compressibility of fluid and shell flexibility.

1 INTRODUCTION

Coupled fluid-structure interaction study of safety class I equipments and in core components is important to demonstrate the safe shut down capability of a nuclear plant for the design basis earthquake. Often designers resort to over simplified procedures for modelling and analysis of these equipments. However all the assumptions of modelling for class I components and equipments subjected to hydrodynamic loads due to sloshing and impulsive motion of the fluid for the design basis earthquake must be suitably justified. This is important in view of the reported tank failures [1-3] due to buckling, elephant foot bulging mode near the tank bottom on account of excessive overturning moment and impulsive pressure loads. Lift off and sliding of tanks and failures of roof due to sloshing have also been reported in the above mentioned review papers. Due to widely separated frequencies of sloshing and impulsive fluid motion, the conventional design and analysis procedure for qualifying tanks is to decouple the problem in which the fluid slosh mass and associated spring stiffnesses along with impulsive mass are used as lumped parameters. However, for large size tanks coupling between impulsive fluid mode and tank frequencies and coupling between excitation frequencies and coupled fluid-tank modes have been reported [1-3]. This results in either higher or lower response prediction with the above simplified method of analysis. Coupling between long period liquid sloshing mode and flexible shell modes for large size tanks is another important issue that needs to be addressed.

The objective of the present work is to evolve an analysis procedure which examines all the assumptions of the modelling for complex tank and vessel geometries such as Pressurised Heavy Water Reactor (PHWR) calandria. The calandria-endshield assembly (fig1) has two compartments known as main shell and sub shell which are connected through the annulus plate. The subshells are enclosed by endshields which support the reactor fuel and coolant accessories through a number of reactor channels in periodic configuration and limit the dose level outside the calandria vault. The endshields are supported through diaphragm plates on a heavy concrete vault structure. Four numbers of calandria keys limit the motion of calandria end shield assembly for the longitudinal motion due to earthquake. The calandria is submerged in vault water. The heavy water moderator inside the calandria induces hydrodynamic load due to sloshing and impulsive motion in the event of an earthquake. It is of interest to estimate the maximum sloshing and impulsive pressure loads for the design of calandria shell and two fast acting independent passive shut down devices which are to activate within first two seconds if the acceleration levels are beyond the specified operating limits.

The sloshing analysis of calandria is complicated due to its horizontal configuration, flexible diaphragm supports, non-flat bottom and multiple compartment geometry with main shell and subshells of different cross-sectional curvatures.This necessitates evaluation of antisymmetric sloshing load along two principal shell axes in transverse and longitudinal directions. Due to small length to diameter ratio of calandria some fundamental shell multilobe modes are important and classical formulae for evaluation of slosh mass, associated spring stiffness and impulsive mass are not directly applicable as these have been formulted for upright fixed base tanks in flexural mode. These complexities need to be resolved for a realistic model of calandria shell. It is also desirable to study the effect of vertical moderator slug motion in symmetric modes.

In the first part of the present work, a three dimensional shell-fluid interaction coupled problem is studied on calandria-endshield shell and moderator fluid models with in-house finite element code FLUSHEL eveloped by Singh [4-5]. Effects of sloshing and calandria shell flexibility along with moderator compressibility are examined. Further modal slosh and impulsive masses of moderator are evaluated from the coupled model. These are used for frequency domain analysis and good comparison between the two analyses is noted.

2 COUPLED MODEL FOR CALANDRIA SHELL AND MODERATOR

Finite element model of calandria with nine noded degenerate shell elements coupled with three dimensional eight noded fluid elements for moderator at 90% level (fig.2) is used for the analysis. The fluid model with acoustic assumptions allows free surface sloshing and coupling with the calandria shell as a boundary condition. As a result of heavy mass the endshields always move together for all the three directions namely transverse, vertical and longitudinal. So all the channel masses with their contents are lumped on endshield tube sheets.The channels account for only 12% volume of the moderator and hence an equivalent homogeneous moderator density is used for the fluid model. Due to low velocities of the moderator under earthquake motion this assumption is justified and has been qualified by parametric variation of moderator density in the present study. The vault water sloshing does not influence the impulsive pressure on calandria because of high submergence and hence it was used as a lumped parameter.The coupled equations of motion with implicit-implicit partitioning of shell and moderator fluid meshes are solved in staggered fashion in time domain with code FLUSHEL. Analyses were carried out for transverse, longitudinal and vertical seismic motions for safe shutdown earthquake condition and the peak responses are obtained. The acoustic speed in moderator is taken as 1433 m/sec. Effect of compressibility was also evaluated with parametric variation of acoustic speed. The impulsive and sloshing pressures were found to be insensitive with respect to the acoustic speed. This permits evaluation of modal masses for the moderator which were numerically derived from this coupled model.

3 SIMPLIFIED MODEL FOR CALANDRIA AND MODERATOR

With the coupled model analysis presented in the previous section all the assumptions of the analysis were confirmed. The simplified model consists of calandria shell and the impulsive and sloshing fluid masses numerically derived from the above coupled model which are used as lumped parameters. This model was used for analysis in frequency domain for all the three direction seismic motions. Ovalling shell and predominant beam modes were identified in the present analysis for different directions.

4 RESULTS AND DISCUSSIONS

4.1 Time Domain Coupled Analysis

The fundamental sloshing and impulsive frequencies of the moderator are 0.462 Hz for transverse motion and 0.44 Hz for longitudinal motion. In case of vertical motion the moderator moves as a rigid body hence the frequency is zero. It is observed from the analysis that the impulsive modes of fluid motion will contribute only as liquid inertia for all the three direction motion of calandria end shield assembly as is evident from impulsive frequencies of 115.7 Hz for transverse motion, 137.4 Hz for longitudinal motion and 52.9 Hz for vertical motion. It is noted that multi lobe shell modes appear for transverse and vertical motion cases and presence of moderator alters the coupled shell fluid frequency in a significant manner. For transverse motion the fundamental frequency drops from 39.4 Hz to 9.57 Hz while for the vertical motion it drops from 37.5 Hz to 9.1 Hz. For longitudinal motion the change in frequency is insignificant (8.78 Hz to 7.59 Hz) due to small mass of moderator entrained with the annulus plate. Tables 1-2 summarise the results of transverse and longitudinal direction seismic motions for cases of flexible shell without moderator sloshing (zero dynamic pressure at free surface), flexible shell with moderator sloshing, and rigid shell with moderator sloshing condition. For transverse motion (table1) the flexible shell solution gives the maximum deflection of 0.239 mm due to the sloshing effect. If sloshing is neglected it results in a lower displacement of 0.175 mm. The rigid shell assumption also results in a lower displacement value of 0.229 mm.The slosh and impulsive pressures do not change significantly for the rigid shell case. The membrane and bending stresses also are not significantly affected with the neglect of sloshing or the rigid shell case. This is due to inherent rigidity of calandria shell assembly in transverse direction. For vertical direction motion the peak sloshing pressure is small (0.00402 MPa) compared to transverse direction motion slosh pressure (0.0135 MPa) and is not affected by the shell flexibility. In this case also the maximum displacement of calandria shell is noted for calandria shell with sloshing case and membrane and bending stresses are not affected by shell flexibility. For the case of longitudinal motion (table 2) the shell flexibility does affect the impulsive pressures significantly (0.0146 MPa compared to 0.0070 MPa). The sloshing pressure is marginally higher for flexible shell case (0.0156 MPa compared to 0.0142 MPa). This is due to inherent flexibility of annulus and diaphragm plate. A peak displacement of 3.73 mm for flexible shell case is noted. In this case the rigid shell solution gives unduly large displacement (5.16 mm) and membrane and bending stresses are also higher compared to the flexible shell case. The neglect of sloshing is again shown to be insignificant for longitudinal motion. This behaviour of calandria endshield assembly denotes that the shell flexibility is only important for longitudinal motion. Fig 3 shows a typical pressure history response for transverse direction motion. It is noted that peak sloshing pressure for lateral motions builds almost near the end of the earthquake at 36.52 sec for transverse motion (table 1) and at 46 sec for longitudinal motion (table 2). The peak impulsive pressure at the bottom portion of the calandria is observed within the strong motion period of earthquake. In the case of vertical motion the peak sloshing pressure occurs at 12.9 sec indicating that the sloshing motion effect is uniform and in higher symmetric modes very little mass is excited. Figs.4-6 show slosh pressure contours at free surface of calandria for three direction seismic motions at times which are close to their respective peak values. It is noted that in transverse direction first mode is significant while in longitudinal direction the peak pressure is at a location midway between main shell centre and annulus plate. This is due to interaction between mainshell and subshell compartments and reflection of free surface waves from the annulus plates. In case of vertical motion the pressure distribution at the free surface is found to be more uniform due to slug motion and higher symmetric modes contribution to the slosh pressure is very small.

It is obvious that the low frequency lateral sloshing phenomena take time to build up and peaks are observed in the decaying portion of earthquake motion while the impulsive pressure peaks (high frequency phenomena) are observed in the strong motion period of the earthquake. The vertical slosh pressure is smaller than lateral sloshing pressure and its frequency is very small due to the major contribution from slug motion (a rigid body phenomenon).

4.2 Frequency Domain Analysis

With the analysis assumptions justified in coupled analysis the moderator fluid was lumped on the shell model by calculating centre of pressure of sloshing moderator, The slosh mass and stiffness were numerically derived from the earlier analyses for all the three motions. In longitudinal direction small amount of vault water and moderator gets added to annulus plate and rest of the moderator mass is added to the heavy endshield tube sheet thus the effective change in frequency of calandria endshield assembly is very small. The fundamental frequencies for transverse and vertical motion cases are found to be with higher shell multilobe modes (7 to 8 lobes across the cross section). The predominant modes are beam type with frequencies in the range of 20.3-20.8 Hz. Frequencies from both the analyses have been found to be in good agreement as shown in table 3. For longitudinal motion the beam mode is predominant with a frequency of 7.8 Hz and nearly all the mass is accounted in this mode. The maximum displacement for transverse excitation is obtained in the calandria mainshell and its magnitude is 0.259 mm (compared to 0.239 mm from coupled analysis). The maximum displacement for vertical excitation is found in the mainshell and its magnitude is 0.23mm (compared to 0.221 mm from coupled analysis). For longitudinal motion the maximum displacement of 3.2 mm (compared to 3.73 mm from coupled analysis) is noticed. The shell frequencies and the maximum deflections obtained by simplified frequency domain analysis are in good agreement with coupled analysis results .

5 CONCLUSIONS

In this work two approaches are followed to evolve models for sloshing analysis in multicompartment horizontal configuration of calandria. The coupled time domain analysis by code FLUSHEL enables modelling of sloshing for all the three direction seismic motions. For complex geometry like calandria this study helps to obtain peak sloshing loads useful for design of shutdown devices and calandria shell and uncertainties in the modelling of sloshing and impulsive masses and coupling effects are investigated. Effect of compressibility is shown to be small by parametric studies. In transverse and vertical directions the first mode of calandria shows shell modes with 7 lobes; however due to very small modal mass in this mode the simplified mechanical model in frequency domain gives results similar to time domain analysis results. The flexibility of calandria is important for only longitudinal motion as shown by the analysis. In the frequency domain analysis more structural details can be suitably modelled along with slosh and impulsive moderator masses. The two approaches of analysis are complementary to each other to get confidence in the final results. Slosh pressures within first two critical seconds of reactor shutdown are very small; hence functional and structural integrity of both shutdown devices is ensured for PHWR design. The present analysis approach can be used for complex tank geometries such as annular and toroidal tanks with internals for hydrodynamic and seismic load qualification.

6 REFERENCES

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Table 1 Comparison of peak responses for transverse motion -coupled analysis

Values within small bracket are node s and values within square brackets are time in sec

	Flexible shell without sloshing	Flexible shell with sloshing	Rigid shell with sloshing
Slosh pressure MPa	--	0.0135 (13) [36.5]	0.0135 (13) [36.5]
Impulsive pressure MPa	0.0133 (43) [15.9]	0.0141 (43) [20.7]	0.0148 (43) [20.7]
Deflection mm	0.175 (205) [12.04]	0.239 (205) [20.7]	0.229 (205) [20.7]
Membrane / Bending stress MPa			
Main shell	2.88/2.00	2.92/3.05	2.92/3.04
Sub shell	2.66/5.01	2.65/5.01	2.58/4.98
Annulus Plate	3.35/5.52	3.71/5.46	3.62/5.43
Diaphragm	2.49/5.49	2.47/5.55	2.44/5.54

Table 2 Comparison of peak responses for longitudinal motion - coupled analysis

Values within small bracket are node s and values within square brackets are time in sec

	Flexible shell without sloshing	Flexible shell with sloshing	Rigid shell with sloshing
Slosh pressure MPa	--	0.0156 (4) [46.0]	0.0142 (2) [32]
Impulsive pressure MPa	0.0143 (57) [10.83]	0.0146 (57) [10.83]	0.0070 (57) [16.6]
Deflection mm	3.65 (116) [10.83]	3.73 (116) [10.83]	5.16 (114) [15.75]
Membrane / Bending stress MPa			
Main shell	15.24/70.14	15.55/71.57	21.26/98.20
Sub shell	20.84/61.70	21.27/62.95	29.14/86.97
Annulus Plate	7.29/152.03	7.44/155.2	10.22/215.06
Diaphragm	0.0/228.2	0.0/232.9	0.0/322.04

Table 3 Comparison of results of frequency domain with coupled time domain analysis

Values in small bracket are from coupled time domain analysis. Shell and beam modes of vibration are indicated for different diections.

	Transverse	Vertical	Longitudinal
Fundamental Frequency (Hz)	9.7 (9.57) shell	10.65 (10.6) shell	7.8 (7.59) beam
Predominant Mode (Hz)	20.3 & 20.6 beam	20.8 beam	7.8 beam
Deflection (mm)	0.259 (0.239)	0.23 (0.221)	3.2 (3.73)

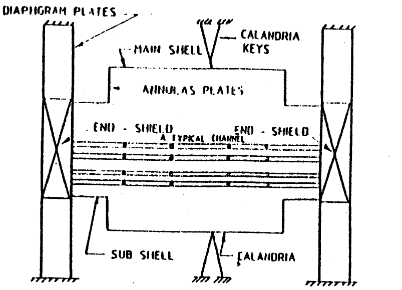

FIG. 1 SCHEMATIC DIAGRAM OF CALANDRIA-END SHELD ASSEMBLY

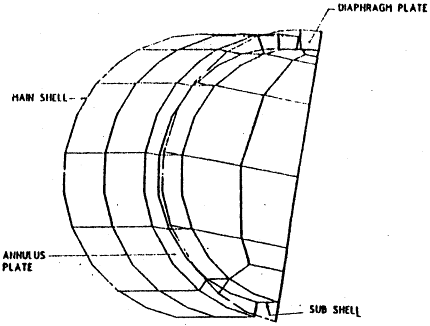

FIG. 2. 500 MWe PHWR CALANDRIA SHELL MODEL FOR SLOSHING ANALYSIS

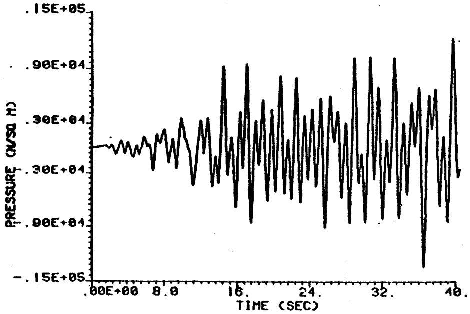

FIG. 3 SLOSH PRESSURE HISTORY IN TRANSVERSE MOTION OF CALANDRIA

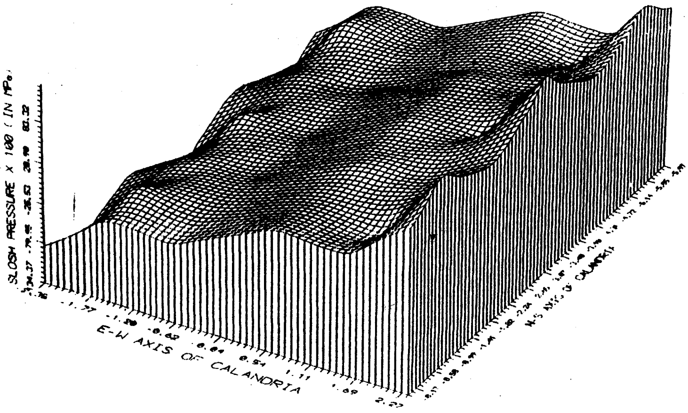

FIG. 4 SLOSH PRESSURE IN TRANSVERSE MOTION

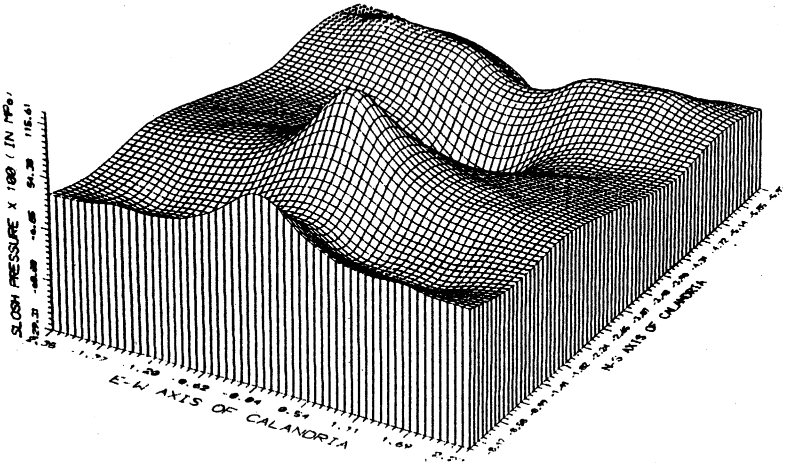

FIG. 5 SLOSH PRESSURE IN LONGITUDINAL MOTION

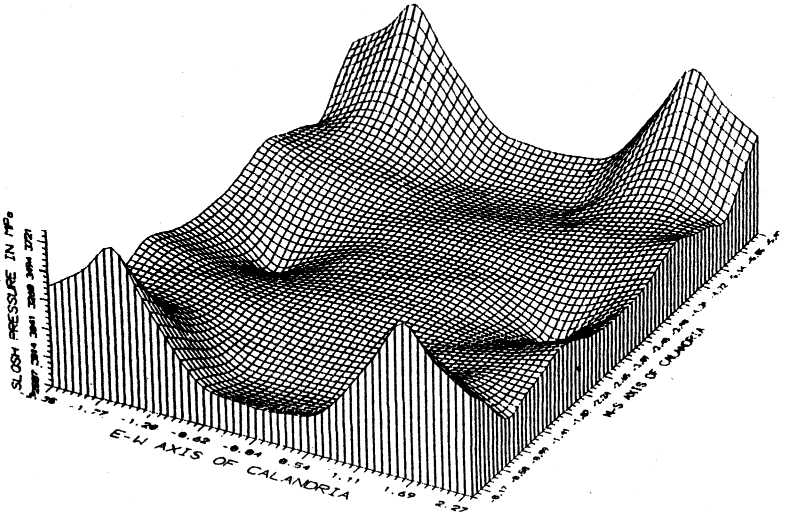

FIG. 6 SLOSH PRESSURE IN VERTICAL MOTION