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BUCKLING BEHAVIOUR OF PFBR MAIN VESSEL AND ITS THERMAL BAFFLES UNDER SEISMIC LOADINGS

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1 INTRODUCTION

The special feature of pool type fast breeder reactor is the usage of very large sized thin shell structures for its reactor vessels. Due to the large diameter to thickness ratio (around 700 to 900), design of these vessels poses challenging structural mechanics problems particularly under seismic loading. An important threat to structural integrity of reactor vessels is the buckling risk during seismic events. The buckling design involves determination of critical buckling load and comparing it with operating load, to ensure that enough safety factors recommended by RCC-MR are available at all loading levels (RCC-MR 1985). The determination of critical buckling load particularly under seismic loading is a complicated task due to dynamic effects, non-axisymmetric nature of loading, material and geometrical nonlinearities, effect of geometric imperfections and boundary conditions and the interaction of different modes of buckling. Based on litrature survey and extensive benchmark studies, the above complexities involved in the buckling analysis have been resolved and subsequent analysis is done for the main vessel and its thermal baffle of Prototype Fast Breeder Reactor (PFBR).

The integrity of main vessel is very important since it forms an important part of primary containment and also carries around 1250 t of radioactive sodium. The integrity of thermal baffles is not very important during SSE (level D) loading. However, for the OBE (Level-B loading), thermal baffles should be designed for meeting buckling criteria since either the loss of their integrity or large displacements may affect the cooling passage for the cold sodium flow and inturn, the temperature of main vessel may rise above the creep temperature. Fig.1 shows schematic sketch of main vessel and its thermal baffles. While the straight portion of main vessel is subjected to shear and bending mode of buckling, its dished end is subjected to shell mode buckling during seismic events. The dynamic pressure developed in annular space associated with the thermal baffles due to fluid structure interaction is the important pressure loading for the buckling of thermal baffles. The seismic analysis performed for the reactor assembly provides necessary input details like shear force, bending moment and dynamic pressure field in the main vessel and thermal baffles. Detailed buckling analysis has been carried out for both these components in order to check the design complaince with RCC-MR. Analysis done for buckling of main vessel under normal loading has already been reported (Damodaran 1991). This paper presents the works done on buckling of main vessel and its thermal baffles under seismic events. The INCA code (CASTEM 1985) has been used extensively for the computation of buckling loads.

2 SEISMIC BUCKLING ANALYSIS APPROACH

The complexities involved in the buckling analysis under seismic loading are handled with following approach.

The equivalent static approach has been followed for the buckling analysis under seismic loadings. The dynamic instability (the coupling between the natural mode and buckling mode) is not considered, since it is found to be insignificant for the seismic type of loadings. Results of seismic analysis are used to determine the static equivalent shear and bending forces and the transient pressure along the vessel wall. There is possible reduction in the buckling load when the dynamic buckling is treated as static buckling (Combescure 1988). This reduction is not considered in the analysis for the sake of simplicity and conservatism. The initial geometric imperfection shape is assumed to be the critical buckling mode with its maximum amplitude equal to 0.5 % of vessel radius. The imperfection and non-axisymmetry are handled by using the COMU elements of INCA code.

For the main vessel, buckling analyses are performed for the straight portion and dished end seperately. In addition, for the straight portion the buckling due to shear & bending loads and the transient pressure are evaluated seperately. The critical stress of the above three modes are compared with the respective maximum stress values computed from the seismic analysis to obtain safety factor available in each mode. The ultimate buckling strength of main vessel is determined by considering the interaction of the three modes. The effect of interaction of axial and hoop loads are not considered, since it is conservative to ignore the interaction effect of these two loads in the case of inelastic buckling (ASME 1989). The net factor of safety is found from the minimum of FS & FS , where FS is the buckling safety factor (BSF) for (shear+axial) mode and FS is the BSF for (shear+hoop) mode. FS and FS are found from the quadratic interaction equations of BSFs of their respective individual modes (ASME 1989).

For the thermal baffles, the dynamic pressure field in the annular space corresponding to the important vibration modes are taken as input. The buckling analysis is done for the normal load (the pressure difference due to the associated sodium levels as shown in Fig.2) and also for dominant dynamic pressure fields. The net safety factor is determined from the linear interaction equation of BSFs for normal and seismic loads. The BSF for seismic load is found from the quadratic interaction equation of BSFs corresponding to the different dominant dynamic pressure fields.

3 ANALYSIS

3.1 Definition of seismic loads

The details of the seismic analysis of reactor assembly has been reported in detail (Ravi 1991). The SRSS pressure values on the main vessel got from this analysis is used for investigating buckling risks. Dynamic pressure around 5 to 6 times of normal pressure is developed in thermal baffles during the seismic loads due to small intervessel gap. For the determination of seismic loading on thermal baffles, a similar analysis with refined meshing in the vicinity of the thermal baffles to get a more detailed pressure distribution was carried out. The analysis was done for horizontal direction using the response spectra shown in Fig.4. The maximum modal differential pressure contributions were calculated and based on this the dominant modes were identified. For the baffle-1 the modes 1,4 5 and 9 are dominant with the maximum modal differential pressures of 0.0079,0.071,0.042 and 0.0074 MPa respectively. For the baffle-2, the modes 2,3,4 and 5 are dominant with the maximum modal differental pressure of 0.032,0.0134,0.0675 and 0.0344 MPa respectively. Only these dominant modal values were used for further calculations. The shape of the pressure distributions corresponding to the above critical modes are shown in Fig.3.

3.2 Results of buckling analysis for main vessel

The buckling analysis of main vessel for its straight portion along with the dished end is done by including the effect of geometric imperfections and plasticity. The critical buckling stress values under shear, bending and hoop loads are evaluated from the analysis with COMU elements of INCA code. These critical buckling stress values are compared with the maximum stress values during OBE and SSE and the computed safety factors for each mode of buckling are given in Table 1. The result clearly shows that shear buckling is the very critical for main vessel (Fig.5 shows the shear buckling mode observed for the main vessel). Interaction between the three buckling modes are evaluated and the net safety factors computed for the main vessel straight portion are also given in Table 1. It shows that, the straight portion with 20 mm thickness can withstand the seismic load of 0.05g OBE and 0.1g SSE without any buckling risk. However, thickness needs to be increased to 30 mm in the case of higher seismic load of 0.06g OBE and 0.2g SSE.

For dished end of main vessel, the normal core load and sodium pressure themselves pose buckling risk at its torus region (Damodaran 1991). The buckling risk is further enhanced during the seismic event because of additional core load due to inertia. The dished end portion with 30 mm thickness is analysed for shell buckling mode due to normal and seismic loads and the results of the analysis are shown in Table 2. It shows that, the dished end with 30 mm thickness meets the buckling limits of RCC-MR code for the normal and the seismic loads for 0.06g OBE and 0.2g SSE.

3.3 Results of buckling analysis for thermal baffles

Thermal baffles are two concentric cylinders connected with main vessel. They act as a passage for cold sodium flow for main vessel cooling and also as a thermal shield to protect the main vessel straight portion against thermal fatigue. Buckling analysis has been done for the normal and seismic loads. For seismic loads, the pressure distribution along the vessel wall in all the dominant modes are considered. The results of analysis indicated that it is not possible to meet the buckling limits for the normal+OBE loading with the simple cylindrical shape of thermal baffles. Analysis is done for different shapes of thermal baffle by providing corrugations in suitable locations. The shape with least fabrication difficulties and also with enough buckling strength (shape-3) has been arrived at. Different shapes considered for the buckling analysis of thermal baffle and their buckling modes under seismic loads are shown in Fig.6. The buckling mode shape of the thermal baffle during one of the dominant mode of dynamic pressure field is given in Fig.7. Table 3 indicates some important results of buckling analysis of thermal baffles.

4. CONCLUSION

Buckling analysis of main vessel and its thermal baffles have been carried out for the normal and the seismic loadings corresponding upto 0.2g SSE (ZPA) by considering all the complexities associated with seismic buckling analysis. For the main vessel, the shear buckling of its straight portion under seismic load is found to be very important failure mode. Analysis indicates that, the straight portion with 20 mm thickness can withstand the seismic load of 0.05g OBE and 0.1g SSE without any buckling risk. However, with 30 mm thickness for the straight portion and also for the dished end, it is possible to avoid buckling risk for the higher seismic load of 0.06g OBE and 0.2g SSE. Thermal baffles with simple cylindrical shape poses high buckling risk during seismic load and its shape has been improved to get higher buckling strength.

Table 1. Buckling safety factor for main vessel straight portion

Loading Normal+ Seismic	Thickness (mm)	Without interaction			With interaction		Required safety factor
		* FS_s	FS_a	FS_h	FS_{sa}	FS_{sh}	
0.05g OBE	20.0	3.25	-	4.97	3.25	2.72	2.5
0.06g OBE	30.0	4.62	-	8.82	4.62	4.09	2.5
0.1g SSE	20.0	1.75	12.10	1.96	1.73	1.31	1.3
0.2g SSE	30.0	1.62	2.71	2.31	1.39	1.32	1.3

* FS_s = Buckling safety factor for transverse shear.
FS_a = Buckling safety factor for bending load.
FS_h = Buckling safety factor for transient pressure.
FS_{sa} = Buckling safety factor for (shear+bending) mode.
FS_{sh} = Buckling safety factor for (shear+hoop) mode.

Table 2. Buckling safety factor for main vessel dished end (with 30 mm thickness)

Loading	Buckling safety factor	Required safety factor
Normal	3.12	2.5
Normal+0.05g OBE	2.64	2.5
Normal+0.1g SSE	2.48	1.3
Normal+0.06g OBE	2.50	2.5
Normal+0.2g SSE	2.00	1.3

Table 3. Buckling safety factor for thermal baffle

Loading Details	Buckling safety factor		Required safety factor
	Simple shape	Improved shape	
Normal	11.02	12.07	2.5
Normal+0.06g OBE	1.61	2.52	2.5

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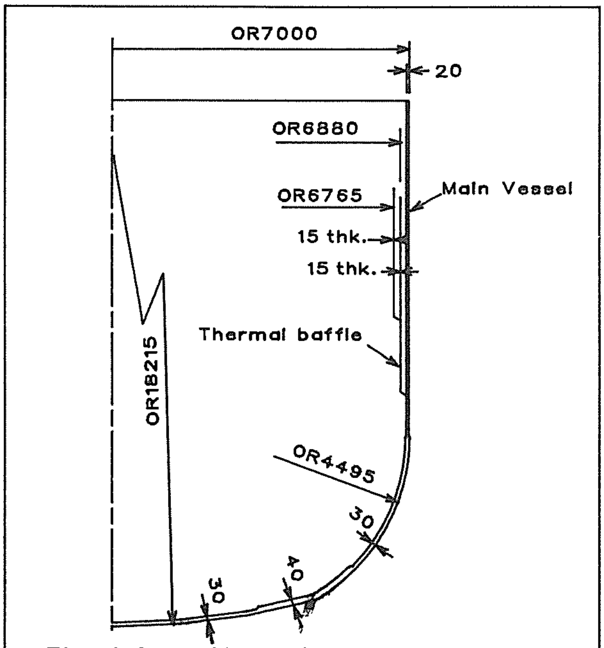

Fig1. Schematic sketch of main vessel and its thermal baffles.

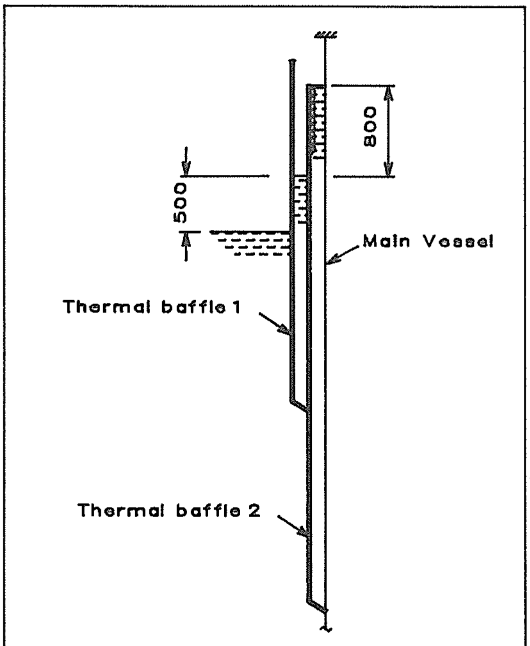

Fig2. Normal pressure loads in thermal baffles.

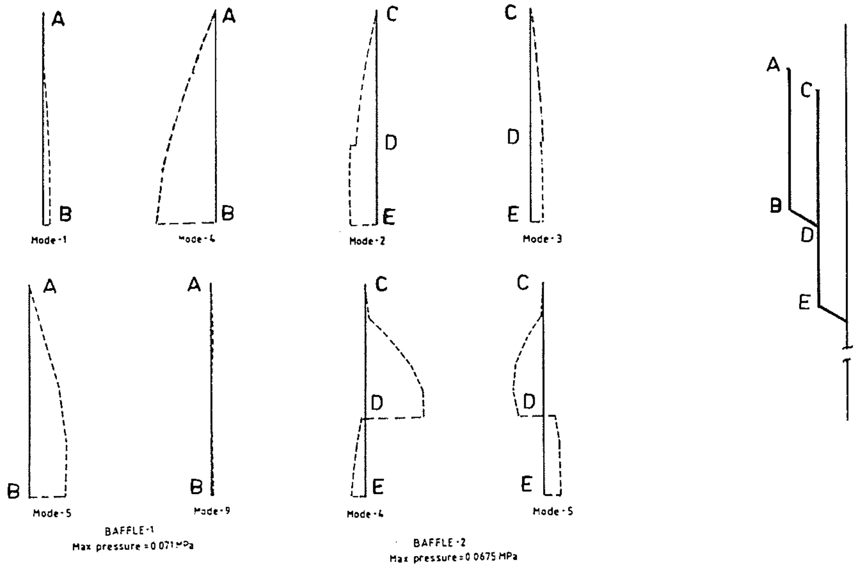

Fig3. Dynamic pressure field in thermal baffles.

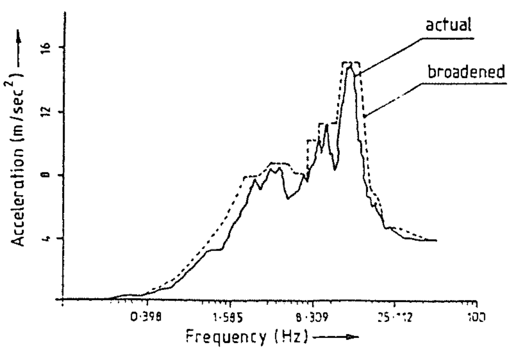

Fig4. Response spectra for horizontal direction

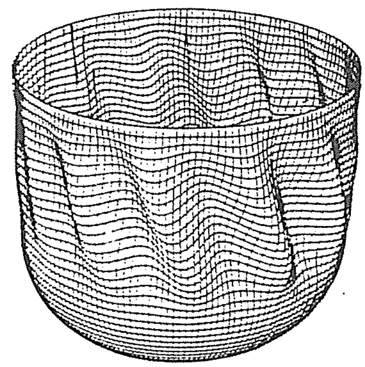

Fig5. Shear buckling mode shape of main vessel

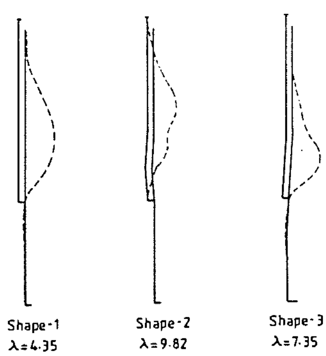

Fig6. Shapes considered for thermal baffles and their buckling modes.

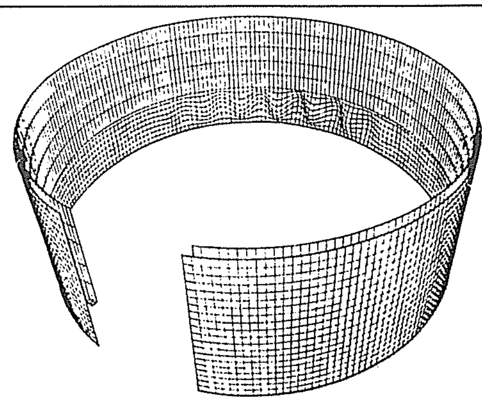

Fig7. Buckling mode shape of thermal baffles.