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Structural assessment of 19 pin fuel bundle during refuelling

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ABSTRACT

The fuel bundles having 19 pins are used in 220 MWe Indian PHWRs. During onpower refuelling the C-ram force along with hydraulic drag acts on fuel bundle as a compressive load. Structural behaviour of bundle, due to axial compressive load with channel supporting conditions, is studied. Buckling, impact and stress analysis is carried out to assess its structural integrity.

INTRODUCTION

The fuel used in the Indian Pressurized Heavy Water Reactor (IPHWR) is in the form of bundles. Each bundle consists of 19 fuel pins arranged in two concentric rings of six and twelve pins around a central pin in 220 MWe PHWR (Fig.1). The fuel pins are thin zircaloy tubes containing small cylindrical pellets (Fig.2). The fuel pins are closed at two ends with endcaps. One endplate is used at each end of 19 pins to keep them in the form of bundle. The fuel pin ends are welded to the endplate. Spacers and bearing pads are used to maintain the interpin spacing and the spacing between the pressure tube and the fuel bundle. One coolant channel houses 12 bundles. The special feature of PHWR is onpower refuelling. Due to onpower refuelling, the hydraulic drag also acts on the fuel bundle along with the ram force which pushes the bundle in the coolant channel during refuelling. The structural compatibility of the bundle with channel supporting conditions against refuelling loads is very essential. Disintegration of fuel bundle inside the channel may impose difficulties in its removal. Therefore, analysis of fuel bundle is carried out to assess its structural integrity.

LOADING AND SUPPORTING CONDITIONS

During refuelling the two fuelling machines(F/M) clamp on two ends of coolant channel. The fuel bundles are pushed into the coolant channel by F/M ram. During refuelling operation, the fuel string is held by the side stop or shield plug at the downstream side. During this operation the hydraulic drag force and the C-ram force of upstream F/M pushes the bundles forward in the coolant channel. This force applies axial compressive load on the fuel bundles. The bundle at the downstream end is supported by the shield plug or side stop during refuelling while the other bundles are supported by adjacent bundles. Following three different load cases are identified for the analysis.

(1) Fuel bundle is supported by shield plug against axial compressive load of 939 Kg at 300 degrees centigrade. In this case the outer ring of endplate comes in contact with the orifice of shield plug, while the central nose of shield plug orifice may touch the bundle (long nose) or may not touch the bundle (Short nose). Both possibilities are considered in the analysis. Case 1a and 1b are considered for short and long nose of shield plug orifice. The possibility of nose piece longer than the shield plug orifice is ruled out.

(2) Fuel bundle is held by F/M side stop (6 pins supported) against axial compressive load of 655 Kg at room temperature. Figure 3 shows the typical shape and position of F/M side stop used for holding the bundle.

(3) Fuel bundle is supported by another bundle against axial compressive load of 1088 Kg at 300 degree centigrade.

MODELLING OF FUEL BUNDLE

The three dimensional finite element model of bundle is prepared to accommodate the geometrical details. The fuel pins are thin zircaloy tubes and 28 fuel pellets are arranged axially in a tube. Since the pellets are discontinuous pieces, some axial gap may exist between the pellets. Hence it is assumed that pellets will not share the load during the structural deformation of fuel pins. Three dimensional beam elements are employed for modelling the 19 fuel pins. The endplates of the bundle are thin plates. Therefore these endplates are modelled using thin shell elements. The inter pin split spacers and bearing pads are modelled using gap elements. In total 612 shell elements, 190 beam elements, 72 gap elements were used in the finite element model. Total number of nodes were 1136. Each node of the model has 6 degrees of freedom. Figure 4a shows the finite element model of one endplate. The finite element model of complete fuel bundle is shown in figure 4b.

STRESS ANALYSIS

The stress analysis for load cases 1, 2, and 3 is carried out [1]. Finite element computer package 'NISA' [2] is used. Material properties, used in the analysis, are shown in Table 1 [3]. Analysis details and results obtained for different load cases are described in the following lines.

(1) In load case 1 the bundle is supported by shield plug against axial compressive load. The outer ring of endplate comes in contact with orifice of shield plug, while the nose piece of shield plug may or may not touch the endplate of bundle. The occurrence of any of these two possibilities is considered in the analysis. The membrane stresses, membrane plus bending stresses for fuel pin sheath and weld between endcap and endplate are shown in Table 2. Table 3 shows the stresses in endplate. It can be seen from table that membrane compressive stresses in outer pin sheaths are dominant in comparison with bending stresses. The magnitude of stresses in inner pin sheaths are less. The stress scenario in weld is different. The welds of outer pins also have higher proportions of membrane stresses but in

the inner pin welds, the bending stresses have high proportions thereby causing part of weld in compression and some part in tension. While the pin sheaths are totally under compression. Overall the stresses in the different fuel pin sheaths and welds are within allowable limit of material [3,4].

As the endplate is very thin and the load is acting normal to its plane, it is expected to bend under pure bending. Maximum stress intensity in endplate is observed at the junction of outer ring with ribs in case the nose of shield plug is little shorter than orifice face. When the nose is at the same level as the orifice face, high stresses are observed at the junction of central rib with that of inner ring. Figure 5a shows the deformation of fuel bundle when it is supported by shield plug.

(2) In the load case 2, the F/M side stop is used for supporting the fuel bundle against axial compressive load. This particular case occurs during refuelling operation at room temperature. The bundle is located in the guide tube during this loading. In the most probable case, two pins of bundle are touching the guide tube. In this case, the side stop positioned to support the pins numbered as O1, O2, O4, O9, O11, O12 while in the extreme possible case (bundle is resting on one pin) the side stop supports pins numbered as O2, O4, O5, O9, O10, O12. Analysis for two different positions of bundle in guide tube is carried out.

The stresses in pin sheath, weld along with the location are shown in table 2. The stresses in fuel pin sheath are mostly compressive membrane stresses. The welds have high magnitude of bending stresses thereby causing part of weld in tension and part in compression. The stresses in pin sheath and weld are within allowable limit of material [3,4].

The stresses in endplate are shown in table 3. In extreme possible case (bundle resting on one pin) the stresses in endplate are 16 percent higher than the most probable case (bundle resting on two pins). The stresses in endplate are less than the allowable values [3,4]. Deformed shape at one end of fuel bundle, supported by side stop, is shown in Figure 5b.

(3) In the third load case the fuel bundle is supported by another bundle in the channel against axial compressive load. In this case, two endplates will come in contact. Due to different possible orientations of two bundles with respect to endplates, the outer ring, inner ring and some part of centrally located rib area will be supported by another bundle.

In this case the stresses in fuel pin sheath and weld are within limit. Bending stresses are not present in pin sheath and weld. Stresses in endplate are negligible as it is not bending due to face to face contact of loaded bundle with another bundle.

BUCKLING ANALYSIS

The buckling analysis is carried out for different supporting conditions. In the first case it is assumed that the bundle is supported by shield plug. Buckling analysis is carried out by eigen value approach. Shield plug supporting conditions are simulated by restricting the part of endplate which comes in contact with shield plug. The axial compressive load is simulated by applying the pressure to the endplate surface. The surface of the endplate, in contact with the ram, is treated as a plane perpendicular to the axis of the coolant channel which remains plane even after loading.

In the second case, the fuel bundle is supported by F/M side stop against axial compressive load. During refuelling the orientation of bundle in the channel is not the same always.

Depending upon the orientation of bundle, the number of pins held by F/M side stop may be 6,7 or 8. The bundle with 6 pins stopped by side stop is likely to give lower buckling load. The location of 6/7/8 pins with respect to endplate will also affect the buckling load due to unsymmetric configuration of endplate. The Buckling loads are evaluated for different orientations of bundle [5]. Minimum buckling loads are given in Table 4. Figure 6 shows the buckled mode of fuel bundle. Analysis is also carried out at operating temperature (300 °C) of reactor. The buckling loads of fuel bundle at 300°C are approximately 16.5 percent less than those at room temperature. It is important to note that these buckling load values are valid only if transverse deformation is freely permitted. If the fuel pin deformation is obstructed then the buckling load will be increased. Under this condition, the fuel pins may develop some plastic deformation if load is high. However, it will be governed by the amount of displacement. Maximum available gap between one of the pin of bundle and guide tube is 1.445mm. For all other pins gap available for displacement is less than 1.445mm. In the bundle one pin can have transverse displacement of 1.445mm (available gap) without any obstruction. For 1.445mm displacement, the stresses in the fuel pin are less than yield stress (Appendix I(1)). The yielding of buckled pin, with limited displacement of 1.445mm, will initiate only, if the load shared by the pin exceeds 536 Kg at room temperature and 294 Kg at operating temperature (Appendix I(1)). Other pins will share higher loads before yielding due to lesser gap available for transverse displacement.

Buckling load is also evaluated for the third case, where the fuel bundle is supported by another bundle. Buckling load for this case is higher than the first and second cases. Buckling loads of fuel bundle, for varying supporting conditions, are listed in Table 4.

IMPACT ANALYSIS

During refuelling, a pair of fuel bundles moving with a velocity of 3m/min. may hit the 12 bundle column in the channel against shield plug. It will cause impact loading to the fuel bundle. The fuel bundle just adjacent to the shield plug will be affected maximum due to limited peripheral support provided by shield plug to the bundle, while all other bundles will be having full face contact on both sides. Conservatively, it is assumed that impact load is shared by the bundle just adjacent to shield plug.

The complex geometry of fuel bundle was not amenable to analytical solution. The finite element technique is used for computing the strain energy in the bundle for particular loading condition. The energy based approach is adopted for carrying out impact evaluation. The strain energy (Appendix I(2)) of the bundle due to axial load is computed in such a way that maximum stress intensity in the bundle corresponds to the yield stress. The kinetic energy (Appendix I(3)) of the bundle is calculated at the time of striking. The kinetic energy of the bundle and strain energy of the bundle are compared. It is considered that if the strain energy of the bundle due to axial load is more than the kinetic energy of the bundle, yielding may not occur. But if the kinetic energy of the bundle is more than the strain energy of the bundle due to axial load, the bundle is likely to go into plastic stage.

The maximum strain energy, the bundle can absorb without yielding is computed based on elastic finite element analysis [6]. It is found that elastic strain energy of bundle due to axial load is more than the kinetic energy of bundle. Therefore any impact during refuelling will not cause the yielding of fuel bundle at ambient temperature as well as at 300 deg C.

DISCUSSION AND CONCLUSION

Structural integrity assessment of the 19 pin fuel bundle, due to axial load arising from C-ram force and hydraulic drag during refuelling, is performed. Stress analysis shows that stresses in fuel pin sheath, weld and endplate are within allowable limits. Analysis suggests that a nose length of shield plug orifice should be shorter than orifice length. During refuelling, precaution may be taken that fuel bundle should rest on two pins in channel to reduce the stresses.

From buckling analysis, it is noted that fuel bundle will remain within elastic limit. There will be no permanent deformation in pins due to the limited space available for displacement. The space constraint and stiffness imparted by the pellets, will increase the buckling load. It is found from impact analysis that yielding is not likely to occur in the fuel bundle.

Hence, it can be said that structural integrity of fuel bundle will be maintained during refuelling.

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APPENDIX - I

(1) Stresses in buckled fuel pin = P/A + Pe/Z
(2) Strain energy in bundle = cP^2K
(3) Kinetic energy = $Wv^2/2g$

A=C.S.area; Z=Section modulus; P=Load; e=lateral deflection; K=Stiffness(load/axial def.); c=prop.const.; v=velocity; W=Weight; g=Gravitational const.

Table 1 Material properties of Zircaloy

	Room Temp	300 °C
E (Kg/sqmm)	9855.5	8224.7
μ	0.295	0.261
YS (Kg/sqmm)	40.3	22.1

E=Young's modulus
μ=Poison's ratio
YS=Yield stress

Table 2 Stresses in fuel pin sheath and weld.

Load case	pin sheath stresses Pm	pin sheath stresses Pm + Pb	weld stresses Pm	weld stresses Pm + Pb	Location of pin
1a Short Nose	-4.00	-4.01	-6.10	-6.16	O6,O7
	-o.22	-0.36	-0.33	-4.31	I4,I3
1b Long Nose	-3.58	-3.58	-5.45	-5.51	O6,O7,C1
	-0.61	-1.16	-0.93	-7.03	I4,I3
2a bundle resting	-5.2	-6.1	-7.9	-17.9	O2,O11
on two pins	-0.5	-1.3	-0.7	-9.6	O5,O8
2b bundle resting	-5.1	-6.0	-7.8	-18.1	O10
on one pin	-5.1	-5.8	-7.8	-16.0	O4
3	-3.0	-3.0	-4.6	-4.6	all pins

Note: Allowable Pm = Sm = 0.67 Yield stress
Allowable Pm + Pb = 1.5Sm = Yield stress

Table 3 Stresses in endplate

Load Case	SI (Kg/sq.mm)	Location
1a	21.0	rib-OR junction
1b	27.6	rib-IR junction
2a	31.2	Near pins O4,O9
2b	36.1	Near pin O2
3	Negligible	-

Note:1. SI=STRESS INTENSITY; IR=INNER RING, OR=OUTER RING
2. Allowable SI(Pm+Pb)=1.5Sm =YS

Table 4 Buckling loads (Kg)

Support condition	RT	300 °C
1 Shield plug		
a) Short Nose	3588.6	2996.1
b) Long Nose	3932.7	3291.6
2 FM side stop		
a) 6 pins held	1624.8	1356.3
b) 8 pins held	2041.9	1704.8
3 FUEL BUNDLE	5438.6	4547.6

RT=ROOM TEMPERATURE

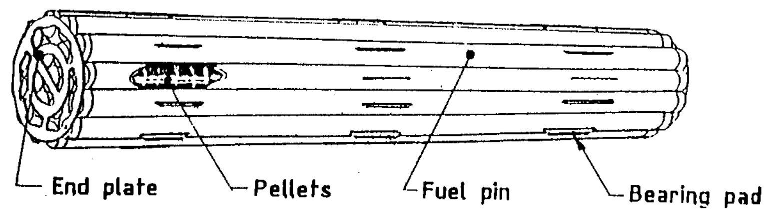

Fig. 1: Isometric view of 19 pin fuel bundle

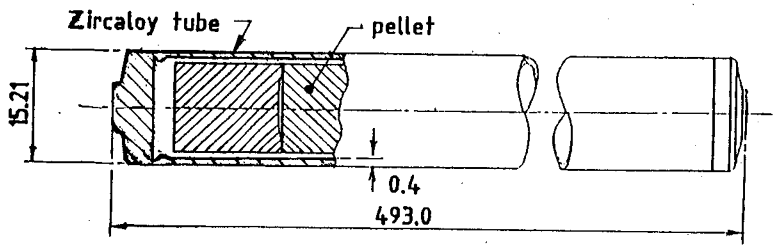

Fig. 2: Geometry of fuel pin

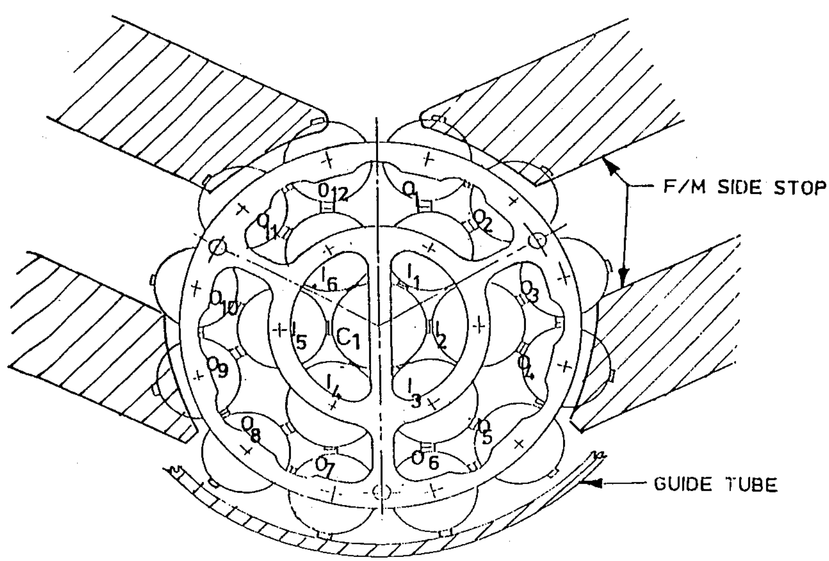

Fig. 3 Location of F/M side stop w. r. t. bundle resting on two pins in guide tube

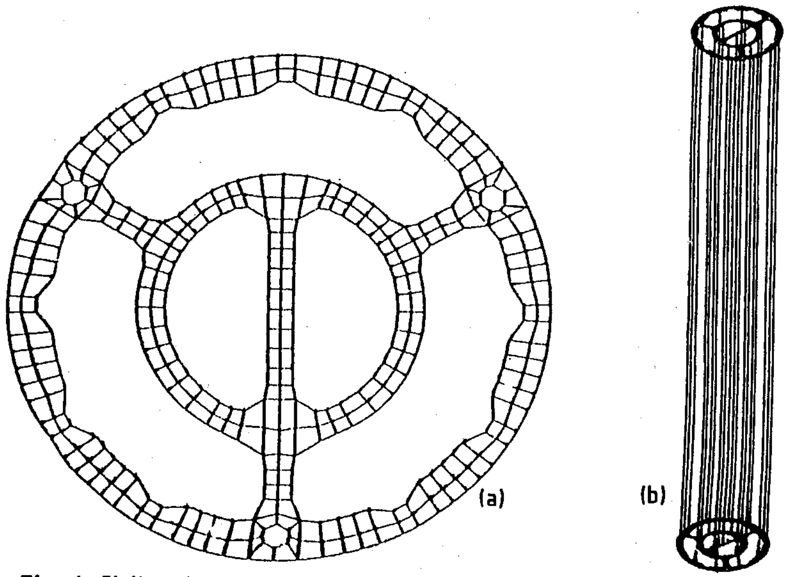

Fig. 4 Finite element model of (a) Endplate (b) Fuel bundle

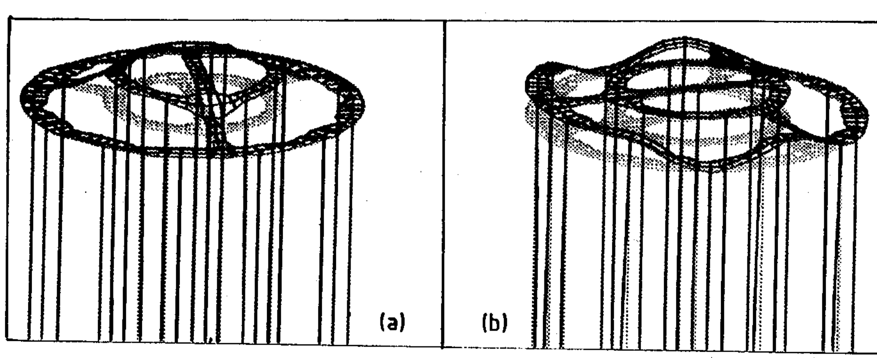

Fig. 5 Deformation of supported end of fuel bundle for (a) Shield plug support (Short Nose) (b) F/M side stop support

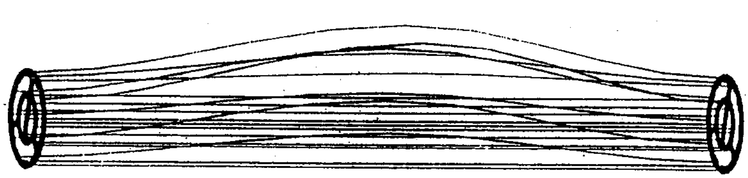

Fig. 6 Buckling of 19 pin fuel bundle