

FUEL BUNDLE END PLATE ANALYSIS BY CODE SPACE

A. G. CHHATRE, M. DAS, S. A. BHARDWAJ, R. S. RUSTAGI

*Department of Atomic Energy, Power Projects Engineering Division,
Homi Bhabha Road, Colaba, Bombay-400 005, India*

The fuel bundles for the Rajasthan Atomic Power Station (RAPS) consist of a close-packed array of 19 elements of about 500 mm length structurally joined by two end plates. For a reactor like RAPS which is heavy water moderated and cooled and uses natural uranium as fuel, the short bundle concept had to be adopted from considerations of fuel burnup, reactivity and fuelling system flexibility (on-power fuelling). The end plate design is such that minimum amount of parasitic material is used and the separation between the bundles is also kept to minimum to avoid flux peaking. The resulting thin end plates however provide excellent resistance to deflection in the vertical plane while permitting differential length changes in the elements. In the reactor, fuel bundles are subjected to various hydraulic, mechanical and thermal loads during their loading into the reactor, irradiation in the core for about two years and finally during discharge into the fuel storage bay. Failure of few end plates was observed during reactor operation in 1975. To investigate into the causes of this failure, a program of theoretical and experimental studies was undertaken.

In order to evaluate the deformation characteristics of the end plate under various loading and support conditions, it is necessary to analyse the fuel bundle as a structure. The computer code SPACE was developed which is capable of performing three dimensional force-displacement analysis. The structure is assumed to be a rigid jointed space-frame consisting of members which are assumed to behave as elastic bodies. The bundle structure was divided into 79 members with 52 nodes. The shear deformation in the member is neglected. The joints of the structure have six degrees of freedom consisting of three translations and three rotations.

The program consists of the main program SPACE and five sub-routines, namely, ANAL, STIFF, M&F, MODIFY and SOLVE. The simultaneous equations obtained from the relationship of the stiffness matrix, displacement matrix and load matrix are solved by using gauss elimination solution.

Three different loading conditions have been studied. The code predictions compare well with the actual simulated tests carried out.

1. Introduction

The fuel bundles for the Rajasthan Atomic Power Station (RAPS) consist of a close-packed circular array of 19 elements of about 500 mm length, arranged in two concentric rings of 6 and 12 elements around one central element. The reactor which is of pressurised heavy water type is characterised by horizontal pressure tubes, natural uranium dioxide fuel and on-power bi-directional fuelling scheme. For such a reactor system, short length fuel bundles are designed from considerations of optimum fuel burnup and reactivity. The elements are structurally joined by two end plates (Fig.1). The design of the end plate is based on use of minimum material in order to gain burnup and also keep separation between two adjacent bundles in the pressure tube to a minimum to avoid the local flux peaking. The thickness of the end plate thus designed is only 1.6 mm which is rigid enough to support all expected service loadings during its life span and at the same time permits differential length changes between the elements.

Failure of a few end plates was observed during reactor operation in 1975. To investigate into the causes of this failure, a program of theoretical and experimental studies was undertaken. A computer code SPACE was developed for the detailed analysis of the end plate deformation characteristics. The paper describes the investigations carried out and the results of the analysis by code SPACE.

2. Description of the Fuel Transfer System

During its short life span in the reactor (about 2 years on an average), the fuel bundle moves past several tubes in the fuel transfer system and is normally pushed by hydraulic rams. To describe in brief the normal sequences of fuel movement, the new fuel bundle is first put manually into the new fuel magazine tube and then passes through the horizontal fuel transfer tube, transfer arm, fuelling machine, reactor coolant channel, shuttle transfer station and at the end of life discharged into the spent fuel bay, all operations being remotely controlled. During these stages in the fuel transfer system, the fuel bundle end plates are subjected to various mechanical, hydraulic and thermal loads including neutron irradiation. The most critical loadings which are likely to cause end plate damage are the following:

- (i) The maximum compressive load on the fuel bundle is of the order of 909 kgs. This is the sum of all hydraulic and mechanical loads that may be imposed on the bundle end plate by the fuelling machine rams. Depending on the support conditions at the downstream end, this loading condition could be serious enough to cause end plate damage.
- (ii) At two stages, the fuel bundles are pushed by rams whose diameters are smaller than that of the end plate outer diameter. As a result, the ram contacts only the inner elements of the bundle. In a fresh bundle when the end plates are ductile, such a pushing will result in relative axial movement of the contacted elements causing bending of both end plates, concave at one side and convex at the other. In an irradiated fuel bundle, however, very little ductility is left and there is possibility of brittle failure of the end plate spokes.

The Code SPACE has been utilised in analysing situations (i) and (ii) above.

3. Structural Analysis

3.1 Program Features

Space frame analysis is ideally suited for structures of complicated nature. The program has inherent versatility in having no restrictions on the location of the joints, direction of the members and direction of loads and supports. The computer code SPACE is divided into five subroutines. The program follows a standard procedure of forming a stiffness matrix of the structure from the stiffness of each of the members [1]. The member stiffness matrix $[K_m]$ which relates the force matrix $\{F_m\}$ and joint displacement matrix $\{\delta_m\}$ is expressed in the form of the following expression:

$$\{F_m\} = [K_m] * \{\delta_m\}$$

The force, displacement and stiffness matrices in the local coordinate system are related to the global coordinate system by standard angular transformation matrix. The load vector required for the analysis is assembled by considering joint loads and members loads separately. The nature of loads on the structure could be concentrated load acting on joints, concentrated load acting on the members in between the joints or uniformly distributed load on the members. The joint loads are read directly from the data cards. In the case of uniformly distributed loads and concentrated loads on members, the fixed end reactions are calculated in the program itself and then equivalent member load vector is added to the joint load vector to obtain the combined load vector.

The simultaneous equations obtained from the relationship of the stiffness matrix, displacement matrix and load matrix are solved by Gauss elimination technique to compute the displacement response of the structure. The fact that the stiffness matrix of a structure is always symmetric implies that one requires to retain only half the matrix including the leading diagonal. In the program, formulation of such a banded stiffness matrix requires no extra effort except that the matrix need be deformed so that the diagonals are stored as vertical columns.

3.2 Fuel Bundle Structural Idealization

For simplicity of analysis, fuel bundle with the 19 elements welded to the end plates is idealised into a frame structure. Elements of the bundle, webs and spokes of the end plate are treated as the members of the structure, which are connected to each other at the joints called nodal points. For the present analysis, the fuel bundle structure has been divided into 79 members and 52 nodes. Figure-2 shows the outlines of the fuel bundle structure with node numbers.

The basic dimensions and design conditions for the fuel bundle structure are summarized in Table-I.

3.3 Boundary Conditions

To properly simulate the fuel bundle sliding condition in the reactor and in the fuel transfer system, the supports of the stiffness matrix model have to match with the actual bundle support. This was achieved by providing rolling supports at the respective nodal points. For simplicity of analysis, the bearing pads on each outer

element over which the fuel bundle slides during its movement in the coolant tube or in the fuel transfer system were assumed to be at the end of the elements instead of their actual locations.

3.4 Loading Cases

Three loading cases were studied as under:

- (i) Case-1: Bundle loaded with 544 kgs. by full face ram head adopter at one end while at the other end the bundle is supported against two side stops contacting six elements (Fig.1). The total load of 544 kgs. which is the maximum ram force was assumed to be equally distributed on the six elements.
- (ii) Case-2: The maximum load that the fuel bundle could experience during service condition is 909 kgs. as brought out in section 2(i). As a worst support condition at this stage only four elements could contact the side stops.
- (iii) Case-3: In this case, the loading conditions as described in section 2(ii) was considered. The maximum load applied on the inner seven elements was taken as the stalled force of the ram which is 272 kgs.

In all the above three cases, analysed by the code SPACE, the self weight of the bundle was assumed to be uniformly distributed over the elements.

4. Results and Discussions

The results of the analysis are presented in Fig.3 where the side view of the outer and inner webs is shown with node numbers, loading and support conditions and the resultant displacements. Table-II gives a summary of results indicating the maximum absolute and differential deformations when the load is applied and the plastic deformation when the load is withdrawn.

It is seen from Table-II that for the loading conditions of case-1, the deformations are within the elastic limit and as such failure of the end plate by such loading is not possible. Simulated type tests at the reactor temperature and pressure conditions have also demonstrated that the end plate is capable of withstanding even twice the designed load (1088 kgs.) without any permanent deformation [2]. Though the above studies were mainly restricted to unirradiated, non-brittle materials, similar bundle strength tests conducted on irradiated bundles [3] showed that even the irradiated fuel bundle end plate is capable of withstanding the design loads.

Results of case-2 loading show that the end plate is getting permanently deformed by about 0.08 mm, which is not likely to cause failure of the end plate.

In case-3, however, the plastic deformation predicted by the Code is 2.65 mm. This loading condition, though abnormal, had actually occurred at RAPS on fresh fuel bundles during initial stages of commissioning and the measured maximum deformation was found to be 2.57 mm. Such abnormal operations are normally detected and care is taken not to load these bundles in the reactor. If however, such deformed bundle is subjected to in-reactor loading conditions, at the end of life when the ductility of the end plate is drastically reduced, even the hydraulic drag force acting on the fuel string would be sufficient to cause failure of the end plate. Similar failure could

also occur with a smaller diameter ram with its stalled force applied on the bundle, while ejecting the fuel bundle out of the shuttle.

5. Conclusions

1. The analysis has indicated that there are no shortcomings in the existing end plate design, so far as normal loading conditions are concerned. The end plate failures encountered during 1975 operations, were probably as a result of abnormal loading conditions, as visualised in case-3. Corrective actions have been planned for incorporating suitable changes in the fuel transfer system and its operation.
2. The computer code SPACK is capable of predicting the deformation behaviour of the fuel bundle end plate with reasonable accuracy.
3. In view of the good agreement between the code predictions and the experimental results, it is felt that use of this code could be extended for analysis of other nuclear structural systems.

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TABLE - I : FUEL BUNDLE DIMENSIONS AND DESIGN LOADS

Bundle diameter, mm	: 81.7
Bundle length, mm	: 495.3
P.C.D. of outer ring of elements, mm	: 63.6
P.C.D. of mid ring of elements, mm	: 33.0
Diameter of elements, mm	: 15.2
End plate thickness, mm	: 1.6
End plate width, mm	: 3.1
Maximum compressive load on the fuel bundle, kgs.	: 909.0

TABLE - II : RESULTS

Loading Condition	Maximum absolute deformation when load is applied, mm	Maximum differential deformation when load is applied, mm	Maximum differential deformation when load is withdrawn, mm
Case-1	0.28	0.13	0.00
Case-2	0.66	0.40	0.08
Case-3	4.22	2.82	2.65

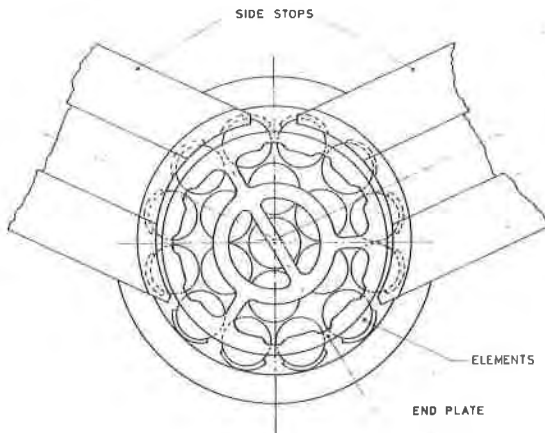


FIGURE-1. DIAGRAM OF A FUEL BUNDLE BUTTING AGAINST SIDE STOPS DURING FUEL TRANSFER

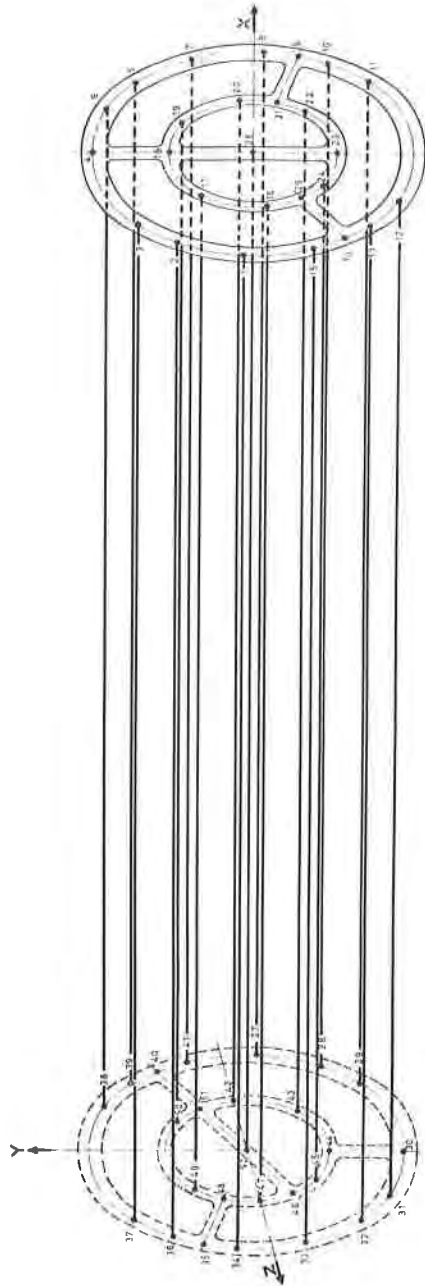
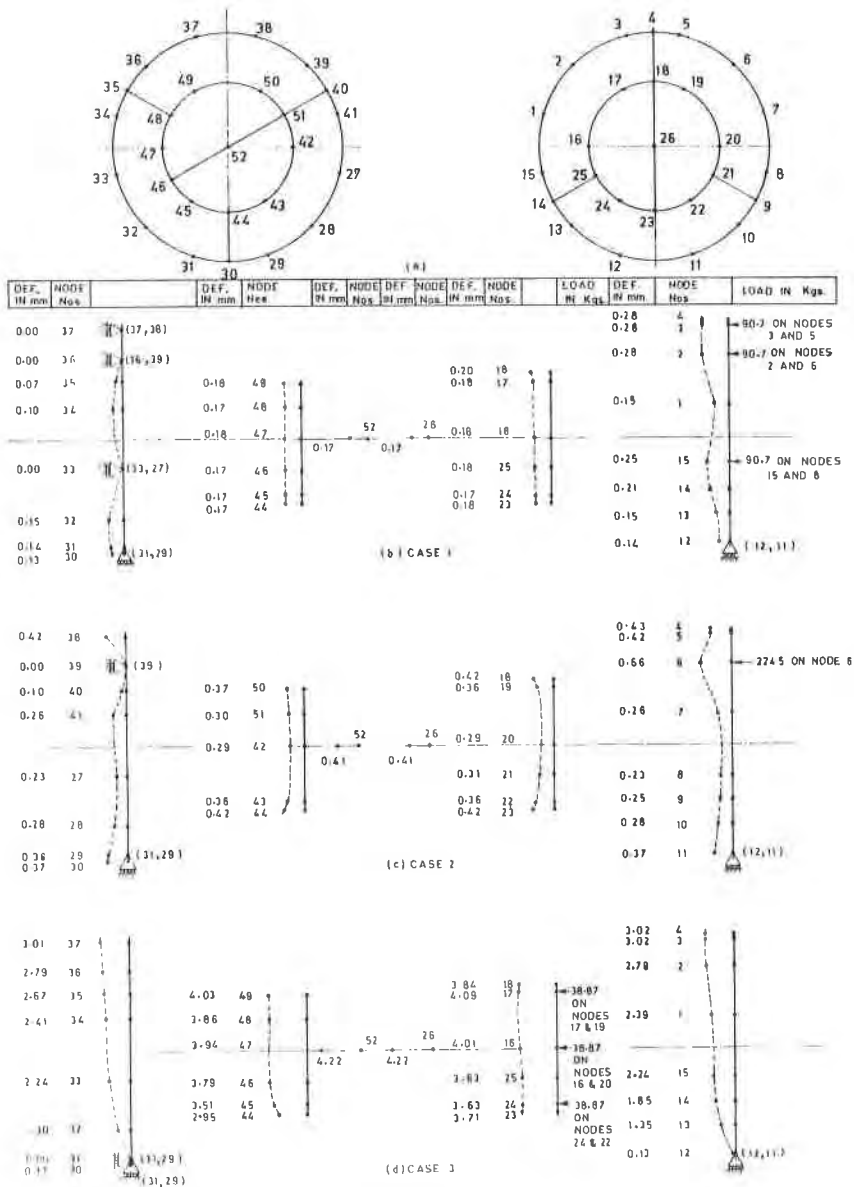


FIGURE --2. FUEL BUNDLE STRUCTURE WITH NODE NUMBERS



a) OVERALL GEOMETRY OF END PLATES WITH NODE NUMBERS
 b), c), d), END PLATES WITH NODAL LOADS, SUPPORTS AND DEFORMATIONS.
 FIGURE-3 AXIAL DEFORMATION OF FUEL BUNDLE END PLATES