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# Developing of FBR core irradiation-induced bowing analysis code RAINBOW

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## ABSTRACT

The RAINBOW code has been advanced by adopting new calculation schemes in order to analyze FBR core irradiation-induced bowing behaviors. The new schemes are :

(1) adding new pad contact model and assembly creep model to reduce computing time,

(2) adding capability to analyze drawing and insertion loads during refueling operations by repeating calculations of core bowing shapes step by step during operations.

The faculty of the RAINBOW was assured by the applications to core bowing analyses.

## INTRODUCTION

It is recognized that irradiation bowing behaviors of fuel assemblies may be one of the most important technical issues for realizing future highly burned FBR cores. Much efforts have been offered in the core design works of "JOYO", "MONJU" and demonstrative FBR's in Japan to evaluate core irradiation bowing phenomenon in real FBR cores.

The RAINBOW code is one of the most progressive computer program which has capability to analyze fully three dimensional behaviors of FBR cores [1]. To provide a computer program applied to FBR core bowing analyses, the international comparison works were organized by IAEA, in which the RAINBOW code had took part in [2].

Through the research and developing work of the DFBR plant in Japan, out-pile experiments have been carried out to simulate core bowing deflection and loads propagation mechanism between subassemblies. Through the research work, it has been assured that the computer codes in Japan have the capability to simulate deflection and loads precisely in elastic modes which is the case of the out-pile simulations [3].

Succeeding the work, the whole core in-pile validation study by the RAINBOW code is required in the next stage. As the RAINBOW code has been developed predict three dimensional behaviors, short cut of the computing time is one of the main issues to be conquered for treating irradiation swelling and creep phenomena.

The drawing and insertion of the fuel assemblies is also one of very important design issues, so that a new scheme was added in the RAINBOW to analyze mechanical equilibrium all through core conditions during drawing and insertion of fuel assemblies.

## BASIC FEATURES OF RAINBOW

### Fuel assembly model

One fuel assembly is modeled by a combination of three dimensional beams which are described by the Finite Element Methodology (FEM), as shown in Fig. 1. Load-pads for lateral spacing are attached at the surfaces of several positions of a hexagonal wrapper tube and are modeled by one dimensional springs that simulate pad deformations when contacts occur between assemblies. For the support conditions of each assembly at the lower end nozzle, a model can be selected from rigid, rotational spring and gap spring models which are shown in Fig. 2.

The stiffness of loads pads is defined by the cross sectional stiffness of hexagonal duct depending on the loads conditions. The coupling stiffness model is introduced for the pad stiffness. Analyses were performed for many contact conditions the results of which are shown in Fig. 3, 4 and 5. The results are drawn in Fig. 6 where stiffness can be judged depending on the contact force balance. The pad stiffness is automatically changed along with the load condition.

### Pad contact model

Reaction forces between neighboring load pads are treated as outer forces so that only one F/A's mechanical equilibrium is solved under the boundary conditions of reaction forces at pads and at the support conditions at the lower end nozzle. Imaginary gap elements are assumed to exist between nodal point i and j of neighboring load pads ( which is shown in Fig. 1), and if i and j points are overlapped in deflection, reaction forces are loaded to those gaps until the overlap vanishes.

This time, improvement of convergence in pad contact model was achieved by introduction of changing forces depending on the overlap level.

## SOLVING SCHEME

Force to deflection equilibrium for each assembly is expressed by the next equation.

$$[K]\ \{u\}_i = \{F\} + \{fg\} \qquad (1)$$

where $[K]$ is a stiffness matrix of one assembly. Contact forces $\{fg\}$ are treated as external form $-[Kg]\{U\}_{i-1}$. Here $[Kg]$ is a stiffness matrix of deflection caused by a contact force. This model uses a small matrix of one F/A that is independent from other assemblies. Calculation procedure is shown in Fig. 7.

## ADVANCEMENT IN CONVERGENCE

### Convergence at pad

Original code used a parameter $\alpha$ defined by the next equation.

$$\{u\}_{I+1}=[K]^{-1}(\{f\}+\alpha\{R\}) \qquad \alpha \ll 1 \tag{2}$$

The $\alpha$ is very sensitive depending on the contact condition, then a calculation easily leads to diverge. We added parameter $\beta$ ($\beta<1$) which can be changed automatically judging the contact condition.

$$\{u\}_{I+1}=[K]^{-1}(\{f\}+\beta\alpha\{R\}) \qquad \alpha \ll 1 \qquad \beta>1 \tag{3}$$

### Creep model

There is a big problem to get creep convergence due to non-linearity in the creep equation because the beam model only treat linear stress conditions.

To get good convergence in creep calculations, a new scheme was introduced in the model. After getting stresses at integration points in a cross-section of a beam ( The beam model of RAINBOW has 12 integration points as shown in Fig. 8 ), a linear stress distribution is supposed keeping equivalent moments in x and y axis. Following equations are introduced to make a linear stress distribution.

$$\hat{\varepsilon}^{C}(x,\ y)=\overline{\varepsilon}^{C}+\frac{\partial\varepsilon^{c}}{\partial x}x+\frac{\partial\varepsilon^{c}}{\partial y}y \tag{4}$$

$\hat{\varepsilon}^{c}(x,\ y)$ : linear creep

$\varepsilon^{c}$:real creep strain in a beam

$$\overline{\varepsilon}^{c}=\frac{\int\varepsilon^{c}dA}{A} \tag{5}$$

$$\frac{\partial\varepsilon^{c}}{\partial x}=\frac{\int\varepsilon^{c}y\ dA}{Iy} \tag{6}$$

$$\frac{\partial\varepsilon^{c}}{\partial y}=\frac{\int\varepsilon^{c}x\ dA}{Ix} \tag{7}$$

The A means section area, the Iy and the Ix mean secondary moment around y and x axis respectively.

## REFUELING ANALYSIS MODEL

Succeeding main procedure of the RAINBOW code, it has been expanded to have a capability to evaluate the insertion and drawing loads of one F/A. Fuels bowing mode and force-equilibrium are solved time-historically when some movements of fuel assemblies occur. Friction coefficient at the contact faces is very important to predict axial forces for drawing or insertion.

## APPLICATION TO THE CORE MOCK-UP TEST RESULT

### Out-pile experiments

The RAINBOW was applied to out-pile experiments data along with other Japanese codes, the results of which were presented at ICONE-4[3]. In the analyses, five bowing experiments were simulated including test cases of increasing center F/A bowing, of compression from core outer wall ( core former ), etc. The deviation of the analyses from the test data was within 20% for displacements and 30% for pad-loads. From the view point of verification, it is concluded that the RAINBOW can be applied to FBR core bowing analysis with accuracy.

### DFBR application

The RAINBOW was applied to the DFBR core bowing analysis to study its capability for a large core problem.

The core bowing modes and analysis conditions are shown in Fig. 9 and 10 after 50 dpa irradiation and 100 dpa irradiation respectively.. The analysis could be performed in 5 minutes by using an IBM personal computer.

## CONCLUDING REMARKS

The RAINBOW code has been advanced by applying new calculation schemes to perform analysis of FBR core irradiation-induced bowing behaviors. This time, improved numerical schemes were added in order to predict large FBR core behaviors including refueling loads.

The RAINBOW showed good convergence in calculations of pad loads and creep strains. Then it requires reduced computing time for treating a large core three dimensional analysis. The code has a capability of predicting insertion and drawing loads during refueling.

## REFERENCES

1. Itoh, K. et. al., 1992. Development of large FBR core deflection analysis code ", Trans. 1992 autumn meeting of the Atomic Energy Society of Japan.

2. Itoh, K. 1990. Mitsubishi results for stages 1A and 2 using the 3-D FEM code. Verification and Validation of LMFBR Static Core Mechanics Codes PartII:288-299

3. Tottori, S. et. al., 1996. A study on fast reactor core mechanics by an ex-reactor test and comparisons with calculations, Proceed. of Int. conf. on Nucl. Eng. 4, New Orleans, 1996, Vol. 2,

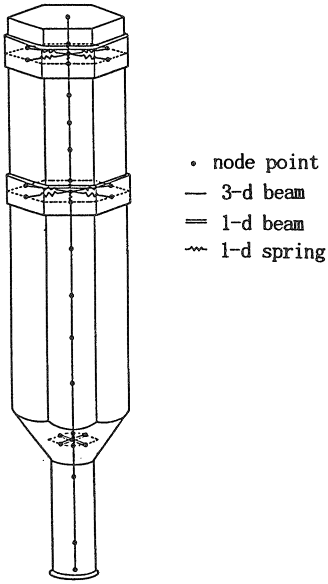
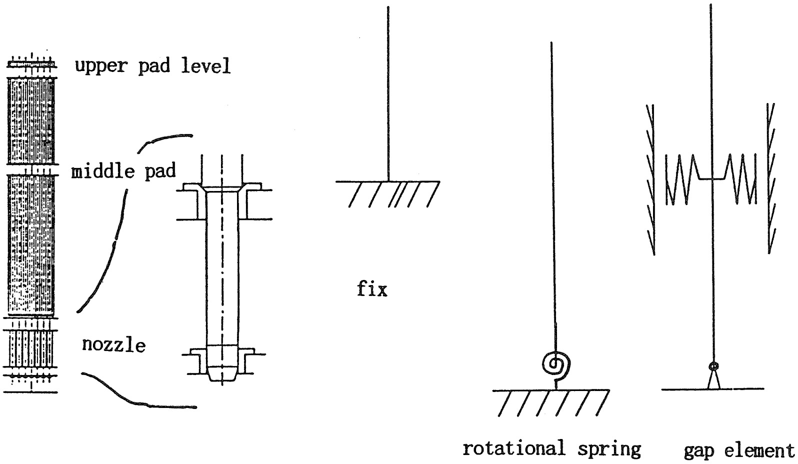


Fig. 1 Fuel assembly model in RAINBOW



fix

rotational spring

gap element

Fig. 2 Nozzle support models

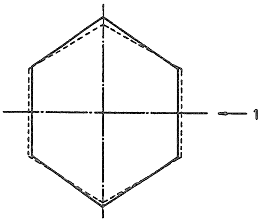
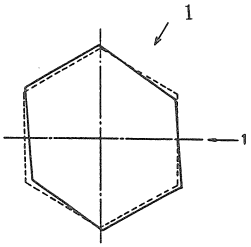
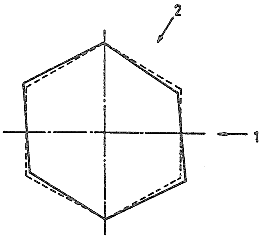


Fig. 3 Pad deflection mode by one load

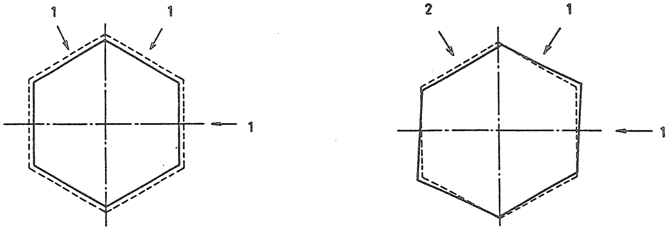


load ratio 1:1



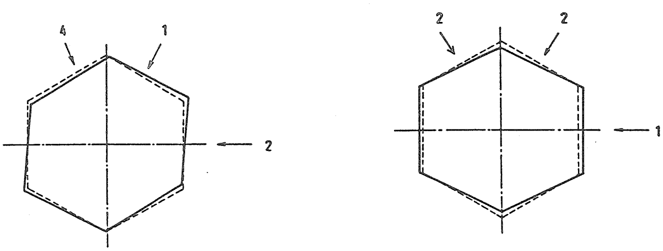
load ratio 1:2

Fig. 4 Pad deflection mode by two loads



load ratio 1:1:1

load ratio 1:1:2



load ratio 2:1:4

load ratio 1:2:2

Fig. 5 Pad deflection mode by three loads

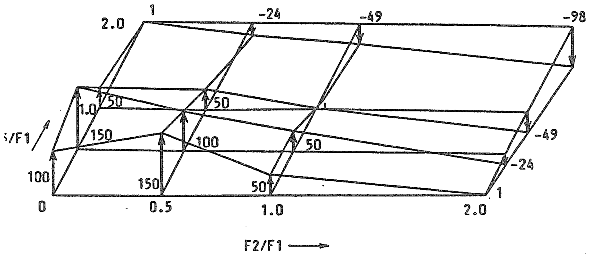
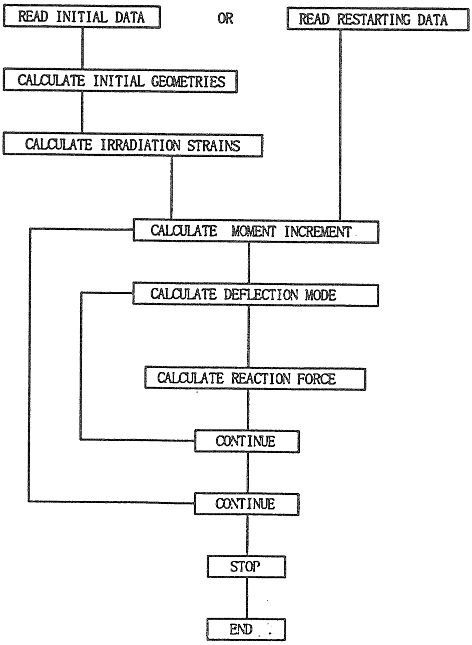


Fig. 6 Pad stiffness chart



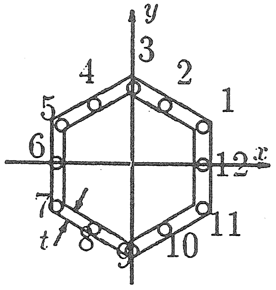
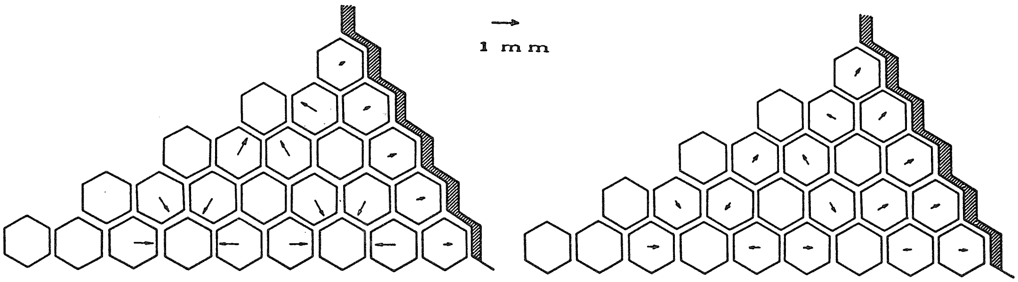


Fig. 8 RAINBOW Integration points

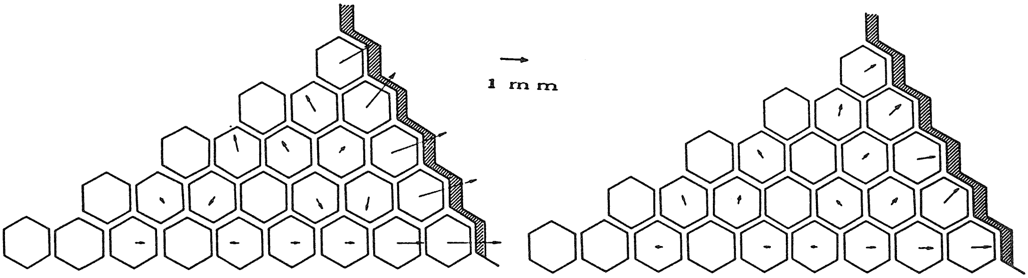
Fig. 7 RAINBOW calculation procedure



upper pad level

middle pad level

Fig. 9 Calculated bowing modes after 50 dpa



upper pad level

middle pad level

Fig. 10 Calculated bowing modes after 100 dpa