SEISMIC RESPONSE ANALYSIS FOR BLOCK-TYPE FUEL HTGR CORE

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SUMMARY

For high-temperature gas cooled reactors with block type fuels, their resistance against an earthquake is not fully ascertained yet. Aseismic design studies and also experiments must therefore be made when such a reactor plant is to be installed in areas of high seismicity.

This report describes analytical and experimental studies on the seismic response of a block-type fuel reactor core, including the followings: aseismic core structure, the calculation model and calculation formulae, the effects of various design variables on response characteristics, and the desired block shape.

Three calculation models have been considered for the seismic vibration of the block-type fuel HTGR core. The first is the impact model, the second "the coupled model", and the third "the mixed model". The calculation has been done with three models, and these results are nearly the same.

The followings were revealed: (1) At low input-wave frequencies, the response value increases with the clearance between the blocks. Beyond a certain point, however, the effect of clearance is nearly negligible. (2) When the blocks are restrained horizontally by keys, the response value decreases with increase of the key stiffness. The key is thus effective in earthquake resistance. (3) The response value increases with block-stiffness, so that short massive blocks are better for earthquake resistance. (4) The response value decreases with increase of the block damping factor. But beyond a certain point, this effect is only small. (5) Stiffness and damping in the restraint mechanism for the reactor core do not have much effect in earthquake resistance.

In addition, a simulation method is described using a computer-graphics in the report.
1. Introduction

In a gas-cooled reactor core, graphite is used as the main structural material. Graphite, compared with steel, is fairly brittle with a low breaking strength, and besides its thermal expansion coefficient is small. The thermal expansion coefficient of graphite is about one third that of steel. Since the periphery of the reactor core is made of steel, provision must be made for absorbing the difference in thermal expansion between the steel periphery and graphite core. And by exposure to the fast neutrons, it undergoes appreciable dimensional change. This dimensional change is then approximately -1 to -2% during the fuel life time. In consequence, the graphite blocks continue to reduce in size during reactor operation, and the meantime, the gap between blocks increases steadily. Moreover, in a high-temperature gas cooled reactor (HTGR), fuel and moderator are embodied in a block (or fuel element), so that in fuel exchange, the block itself must be removed. There then arises the need for its easy replacement. During the lifetime of the reactor in operation, the tight assemblage is thus difficult, so that the usual practice is their arrangement with gap in horizontal direction. Under this situation, however, structural integrity of such "loose" reactor core, at the time of a major earthquake, has not been confirmed yet.

Reactor so far with the block-type fuel have been or are being constructed on the seismic zones with none or little seismicity, and so seismic response analysis or other consideration were hardly made on their design. In this connection, for the unit I of the Japan Atomic Power Company (JAPC) Tokai power station in Japan, the vibration test with a simulated reactor core was made, but only to confirm integrity of the reactor core [1].

One of the most difficult problems in the design of a block-type fuel HTGR is in its aseismic construction. The vibration tests and analyses of core are now performing in the General Atomic Company (GAC) [2], [3]. In the Japan Atomic Energy Research Institute (JAREI), design studies for the Experimental Multi-purpose HTGR were started about 5 years ago, and main emphasis has been on its aseismic aspect.

In the present report, descriptions were concerned to the block-type fuel core, calculation models and formulae, effects on vibration of that core various variables, including between-blocks gap, input acceleration wave, between-blocks stiffness between-blocks and-support-plate stiffness, restraint-structure, block stiffness, block damping factor, restraint-structure damping factor, and friction, and finally the desired block shape.

2. Structure of Reactor Core

The block-type fuel core of a HTGR is such as in Fig.1, which shows the HTGR being developed in JAERI. The reactor core is enclosed in a core barrel, horizontally restrained at the top with an orifice block of a heat-resisting alloy, while the bottom is restrained similarity with a core support plate through keys. Then in the periphery, the core is restrained by the core barrel. Fuel blocks in the core are generally connected together in vertical direction with three dowel pins, but in the horizontal direction they are
loose with gap between them.

Concerning the horizontal arrangement, as shown in Fig.2, one type is not restrained at all, while the other is restrained by key and keyway. Nuclear and thermal characteristic are better in the former type than in the latter. Moreover, manufacture of the blocks with key and keyway is difficult. As thus seen, if integrity of the block-type fuel core against an expected major earthquake in the installation area can be retained without the key and keyway, the loose type is far better.

In the periphery of a block-type fuel core, the fixed reflector in block form adjoins the core barrel certain restraint. In the unit 1 of the JAPC's Tokai power station and the Fort St. Vrain reactor, restraint bars penetrate through the fixed reflector, thereby transmitting seismic force from the reactor core to the external barrel [4]. Integrity of this scheme in an earthquake is going to be confirmed, and it is incorporated in the large HTGR and preliminary design of the Experimental Multi-purpose HTGR [5].

3. Calculation Model and Formulae

3.1 Model

In the block-type fuel core, this group of blocks extends in so-called three dimensions as shown in Fig.3. In the present study, the following simplified models as shown in Fig.4 - 7 for calculation will be considered.

(1) The blocks at the top are restrained the orifice block with some stiffness and damping.
(2) The blocks at the bottom are restrained the core support plate with some stiffness and damping.
(3) The blocks are restrained three dowels and dowel pins with some stiffness and damping.
(4) The blocks in the core periphery are restrained with the restrained structure with some stiffness and damping.
(5) Frictions exist between blocks as shown in Fig.5.
(6) It can be conceivable two models for the mass of blocks:
   (i) each blocks are lumped mass (L-mass type),
   (ii) each blocks are consistent mass (C-mass type).
(7) It can be conceivable three models for the impact phenomena as shown in Fig.6:
   (i) coupled model (R-impact type),
   (ii) impact model (I-impact type),
   (iii) mixed model (M-impact type).
(8) Six calculation models can be conceivable according to above (6) and (7) combination. That are:
   (a) L-R model (Lumped mass - Coupled type model)
   (b) L-I model (Lumped mass - Impact type model)
   (c) L-M model (Lumped mass - Mixed type model)
   (d) C-R model (Consistent mass - Coupled type model)
   (e) C-I model (Consistent mass - Impact type model)
3.2 Formulae

3.2.1 General Formulae

In Fig. 3-5, the equation of motion for block \( i \); at the core center, with its position in absolute coordinate as \( Y \), is then given as,

\[
C_{ij} (\ddot{Y}_i - \ddot{Y}_j) + K_{ij} (Y_i - Y_j) + C_{kij} (\ddot{Y}_k - \ddot{Y}_i) = -K_{ij} (Y_i - Y_j)
\]

\[
\pm F_{fij} = -F_{kij} = -M_i \ddot{Y}_i + F_p
\]

(1)

Where, \( F_p \) is the force from surrounding mass points. With \( Y \) as the local coordinate from the core barrel instead of \( Y \), and hence \( Y_i = Y_i - Y_0 \), eq.(1) takes the following form:

\[
M_i \ddot{Y}_i + C_{ij} (\ddot{Y}_i - \ddot{Y}_j) + K_{ij} (Y_i - Y_j) + C_{kij} (\ddot{Y}_k - \ddot{Y}_i) = -K_{ij} (Y_i - Y_j)
\]

\[
\pm F_{fij} = -M_i \ddot{Y}_i + F_p
\]

in eqs. (1) and (2) suffix zero mean the core barrel, and hence, evidently \( Y_0 = Y_0 \). The equation of motion for a block \( i \) adjoining the core barrel, with stiffness coefficient and damping coefficient of the restraint structure as \( K_{B1} \) and \( C_{B1} \) respectively, is similarly given as,

\[
M_i \ddot{Y}_i + C_{B1} \ddot{Y}_i + K_{B1} Y_i + C_{ij} (\ddot{Y}_i - \ddot{Y}_j) + K_{ij} (Y_i - Y_j)
\]

\[
+ C_{kij} (\ddot{Y}_k - \ddot{Y}_i) = K_{ij} (Y_i - Y_j) - F_{fij} - F_{kij} = -M_i \ddot{Y}_i + F_p
\]

(3)

3.2.2 Coupled Model

In eqs.(2) and (3), if the mass \( i \) is in coupled state with its surrounding masses, \( F_p \) are given as,

\[
F_p = \left\{ \sum_{j=1}^{s_c} C_{ij} (\ddot{Y}_i - \ddot{Y}_j) + \sum_{j'=1}^{s_d} K_{ij} (Y_i - Y_j) + S_{ij} \right\}
\]

(4)

and

\[
F_p = \left\{ \sum_{j=1}^{s_c} C_{ij} (\ddot{Y}_i - \ddot{Y}_j) + \sum_{j'=1}^{s_d} K_{ij} (Y_i - Y_j) + S_{ij} \right\}
\]

(5)

Concerning the effect of gap between blocks, as shown in Fig.7 the three different models are conceivable.

(1) Model-A: no restraint in the gap

In Fig.7(a), when the two adjoining masses \( i \) and \( j \), adhere together, there exist stiffness coefficient \( K_{ij} \) and damping coefficient \( C_{ij} \) in eqs.(4) and (5). And if they do not, both the values are zero.

\[
K_{ij} = C_{ij} = 0 \quad ; \quad Y_i - Y_j \geq -S_{ij}
\]

\[
K_{ij} = C_{ij} \quad \left\{ \begin{array}{l} Y_i - Y_j < -S_{ij} \\ \end{array} \right. \]

\[
S_{ij} = \sigma_{ij}
\]

(6)

(2) Model-B: some restraint in the gap
In Fig.7(b), when the masses i and j adhere or do not, the \( K_{ij} \) and \( C_{ij} \) in eqs.(4) and (5) take the corresponding different values.

\[
\begin{align*}
K_{ij} &= K_{ij}^{(0)}, \quad C_{ij} = C_{ij}^{(0)} \\
\hat{\sigma}_{ij} &= 0 \\
\hat{\sigma}_{ij} &= \hat{\sigma}_{ij}^{(0)} \\
\hat{\sigma}_{ij} &= \hat{\sigma}_{ij}^{(0)} \\
\end{align*}
\]

\( : \quad \gamma_i - \gamma_j \geq -\hat{\sigma}_{ij} \quad \) \quad \( : \quad \gamma_i - \gamma_j \leq -\hat{\sigma}_{ij} \quad \) \quad \( : \quad \gamma_i - \gamma_j < -\hat{\sigma}_{ij} \quad \)

(7)

(3) Model-C: some restraint in the gap with limitation

In Fig.7(c), if the two masses adhere or do not, the \( K_{ij} \) and \( C_{ij} \) in eqs.(4) and (5) are different, correspondingly. When the masses i and j are separated beyond a certain distance, however, both the values become zero.

\[
\begin{align*}
K_{ij} &= C_{ij} = 0 \\
\hat{\sigma}_{ij} &= 0 \\
\hat{\sigma}_{ij} &= \hat{\sigma}_{ij}^{(0)} \\
\hat{\sigma}_{ij} &= \hat{\sigma}_{ij}^{(0)} \\
\end{align*}
\]

\( : \quad \gamma_i - \gamma_j \geq 0 \quad \) \quad \( : \quad 0 > \gamma_i - \gamma_j \geq -\hat{\sigma}_{ij}^{(0)} \quad \) \quad \( : \quad \gamma_i - \gamma_j < \hat{\sigma}_{ij}^{(0)} \quad \)

(8)

As seen, above equations are non-linear, and of these three models, Model-1 can apply to the motion of blocks when there exists some gap between them in horizontal direction. And Model-B and C are applicable to the case when the adjoining blocks are joined together with key and keyway.

3.2.3 Impact Model [6]

In the impact model, the impulse and momentum technique for the collision is used. Velocity and the collision force after collision are calculated from the impulse-momentum equation.

\[
\begin{align*}
V_{i1} &= \frac{(m_iV_{i1} + m_jV_{j1}) - e m_i (V_{i1} - V_{j1})}{m_i + m_j} \\
V_{j1} &= \frac{(m_iV_{i1} + m_jV_{j1}) - e m_j (V_{i1} - V_{j1})}{m_i + m_j} \\
F &= \frac{(V_{i1} - V_{j1}) (1 + e)}{t_c} \frac{m_i m_j}{m_i + m_j} \\
\end{align*}
\]

(9)

3.2.4 Mixed Model [7]

This model is a combination of Impact and Coupled model. In eqs.(2) and (3), \( F_p \) are given as

\[
F_p = \begin{cases} 
K_{ij} (\gamma_i - \gamma_j) + \frac{K_{ij} (1 - e)}{1 + e} (\gamma_i - \gamma_j) : \dot{\gamma} \geq 0 \\
K_{ij} (\gamma_i - \gamma_j) - \frac{K_{ij} (1 - e)}{1 + e} (\gamma_i - \gamma_j) : \dot{\gamma} \leq 0 
\end{cases}
\]

(10)
3.2.5 Relation between Coefficient of Restitution and Damping Coefficient [8]

The relation between the coefficient of restitution and the damping coefficient will be given on the assumption.

3.2.6 Comparison of Impact Model

The calculation has been done with above three models, and these results are nearly same as shown in Fig.8.

4. Calculation Results

In the paper, the calculation has been done with Lumped mass - Coupled type model. The following were revealed (refer to Fig.9).

1. In the low range of input wave frequencies, the response acceleration increases with increase of the gap between blocks. At higher frequencies, occurrence of maximum value then shifts to lower values of the gap. Beyond a certain point, however, the effect of between-blocks gap is almost negligible as shown in Fig.10.

2. The response value increases with input wave frequency, and reaches a maximum at the certain point, it then decreases gradually as shown in Fig.11.

3. When the blocks are restrained horizontally such as key and keyway, the response value decreases with increase of the between-blocks key stiffness. This mechanism by key and keyway is beneficial in earthquake resistance.

4. Response value in the vicinity of the core support plate become smaller, the higher stiffness between blocks and the plate is thus beneficial in earthquake resistance.

5. Stiffness in the restraint structure influences little the response acceleration, velocity and compressive stress, with the exception of block displacement.

6. The response value decrease with increase of the block damping factor. But beyond 0.1, there is only little effect.

7. The damping factor in the restraint structure has only little effect on the response value of blocks.

8. The response value increases with stiffness of the blocks. Their stiffness is thus better to be small for the constant weight; and vice versa.

9. The response value of a block core with random weights and stiffnesses of the blocks are within the value for smallest and largest block cores.

10. The response value changes with the friction force, but the larger friction force is generally not desirable for the aseismic structure.

Moreover mechanical properties change with irradiation dose, therefore in the detail calculation, it is necessary to consider these effects.

5. Vibration Test

One, two and three-dimensional scaled core models, as shown in Fig.12, have been testing and will be testing for HTGR core integrity in the earthquake. Main concerns of tests are;

1. Integrity of the fuel elements and the core support structure,
(2) maintaining the insertion of control rods or reserved shutdown materials at the expected major earthquake.

The tests results will be presented at the conference.

6. Graphic Simulation

A graphic simulation using a computer-graphic display has been doing as shown in Fig.13. The simulation film will be presented at the Conference.

[Nomenclature]

\[
\begin{align*}
C & : \text{Damping coefficient} \\
e & : \text{Coefficient of restitution} \\
F & : \text{Force} \\
F_f & : \text{Friction force} \\
h & : \text{Damping factor, } 2h\dot{\omega}=C/m \\
K & : \text{Stiffness coefficient} \\
m & : \text{Mass of block} \\
t_c & : \text{Contact time} \\
v_{10} & : \text{Velocity before collision} \\
v_{11} & : \text{Velocity after collision} \\
y & : \text{Displacement in absolute coordinate} \\
y_c & : \text{Displacement from core barrel} \\
\dot{y}, \ddot{y} & : \text{Velocity} \\
\dddot{y} & : \text{Acceleration} \\
S & : \text{Gap between blocks} \\
\omega & : \text{Natural frequency, } \omega=\sqrt{K/m}
\end{align*}
\]

References


Fig 1 Vertical cross section of the reactor

Fig 2 Fuel element arrangement

(a) Flat block
(b) Block with key and keyway

Fig 3 Calculation model for friction

$ F_{fr} = 0 \quad |y_1 - y_2| < \delta_d $ 

$ F_{fr} = F_{frd} \begin{cases} |y_1 - y_2| \geq \delta_d \\ y_1 - y_2 > 0 \end{cases} $ 

Fig 4 Calculation model

(a) Plane view
(b) Coupled model
(c) Impact model
(d) Mixed model

Fig 5 Block plane arrangement and calculation models
Fig. 12 Vibration test of one-dimensional scaled core model

Fig. 13 Graphic simulation of a HTGR core vibration