Numerical Analysis of a Concrete Biological Shielding Wall under Neutron Irradiation by 3D RBSM

Daisuke Kambayashi\(^1\), Hiroshi Sasano\(^2\), Shohei Sawada\(^3\), Kiyoteru Suzuki\(^4\) and Ippei Maruyama\(^5,6\)*

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Abstract
In nuclear power plants, concretes used for biological shielding walls are exposed to radiation such as neutrons and gamma rays over the long-term operation of the plant. Previous studies have reported that neutron irradiation causes aggregate expansion due to the metamictization of quartz and feldspar leading to reduced density and a loss of the compressive strength and Young’s modulus of the concrete. Therefore, it is crucial to understand the current state of a concrete biological shield (CBS) and predict its future soundness. In this study, a rigid-body spring model, which can easily evaluate fracture behavior by using springs between each element, is used to conduct numerical analyses on a CBS. A three-phase (mortar, aggregate, and interfacial transition zone) model of a 2000 mm thick CBS is used to investigate the varying deformation responses depending on the presence or absence of reinforcing bars (rebar), creep, and an inner steel plate with five types of analyses, i.e. analysis to understand the impacts of temperature distribution, reinforcement bars, an internal steel plate, and creep of mortar. The results show that cracking and delamination occur inside the CBS, resulting in a lack of cracking on the outside. They also show that the cracks are reduced by rebar and creep, resulting in cracks extending from the innermost edge to a depth of approximately 150 mm.

1. Introduction
Aging management of concrete structures in nuclear power plants is often planned based on knowledge of general structures. Many studies such as by Graves et al. (2014) have been conducted on the durability and maintenance of concrete structures in the general environment. However, the deterioration of concrete members in nuclear power plant facilities under neutron and gamma irradiation has not been fully investigated. There is increasing attention on the effects of neutrons and gamma rays on concrete structures for the long-term operation of nuclear power plants, including special inspections in the fortieth year in Japan and license renewals for sixty- and eighty-year operation in the United States. There are needs to increase the lifetime of operating nuclear power plants under the conditions that capital costs for new plants is increased and social environments posed on the construction of new plants.

It has been reported that the neutron fluence in nuclear power plant buildings is particularly high at the reactor pressure vessel side of concrete biological shield (CBS) walls in pressurized water reactor plants (Field et al. 2015; Maruyama et al. 2017). These CBS walls are characterized by their cylindrical structure and support the reactor pressure vessel (Fig. 1). From the perspective of aging management, the inside of the wall is difficult to access, diagnose, and repair, and is very challenging to replace.

The effects of neutrons on concrete were reviewed by Hilsdolf et al. (1959), and recently Field et al. (2015) compiled results on neutron fluence and property changes. Maruyama et al. (2017) conducted accelerated irradiation tests on concrete specimens in Japan and evaluated the physical properties. The deterioration mechanism of concrete under accelerated aging conditions is the expansion of aggregate due to density reduction through the metamictization of quartz and feldspar by neutron irradiation and cement paste shrinkage due to dehydration caused by gamma ray heating. Interested readers may refer to the results of a Japanese project.

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1 Master course student, Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan.
2 Graduate Engineer, Ove Arup & Partners Japan Ltd., Tokyo, Japan.
3 Group Leader, Nuclear Power Department, Kajima Corporation, Tokyo, Japan.
4 Senior Researcher, Nuclear Safety Division, Mitsubishi Research Institute, Inc., Tokyo, Japan.
5 Professor, Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan. *Corresponding author, E-mail: i.maruyama@nagoya-u.jp
6 Professor, Graduate School of Engineering, The University of Tokyo, Tokyo, Japan.
investigating the deterioration of concrete (Ishikawa et al., 2019; Maruyama et al., 2017; Maruyama et al., 2016, 2018; Maruyama and Muto, 2016).

To estimate the deterioration due to neutron irradiation of a CBS, Le Pape (2015) studied the stress–strain distribution of a cylindrical concrete member based on elasticity theory, by assuming the neutron fluence distribution in the member according to the shielding effect of the concrete and applying the corresponding expansion of the concrete. The maximum expansion strain was set as approximately 4 mm/m. It was noted that the expansion of the concrete inside the CBS creates a tensile stress on the outside of the CBS.

Bruck et al. (2019), using the finite-element method, modeled a portion of a symmetric CBS subjected to a temperature distribution, modeling the change in neutron fluence with time and changes in the physical properties of the concrete. The distribution of stresses and cracks inside the members were calculated using incremental analysis. The amount of fluence at the inner surface was determined to be $6.1 \times 10^{19}$ n/cm² ($E > 0.1$ MeV) for eighty years of operation. It was found that the expansion of the inner concrete due to neutron irradiation causes cracks in approximately half of the cross section of the CBS from the outer surface.

In this study, based on the experiments conducted by Maruyama et al. (2017), the concrete located at the inner surface and exposed to a high neutron fluence is modeled considering the coarse aggregate, mortar, and interfacial transition zone (ITZ). The rigid-body spring model (RBSM), which can explicitly consider the expansion of the coarse aggregate and the resulting cracking of mortar as greatly affected by the stress field at the expansion of aggregate, is used to analyze the damage and deterioration of the cylindrical structure. The deterioration and damage of concrete inside the CBS from neutron irradiation are discussed from the viewpoint of structural integrity assessment. As will be described in the following, cracking and delamination occur inside the CBS, with the extent reduced by rebar reinforcement and creep and extended by the inclusion of an internal steel liner plate.

2. Method and models

2.1 Outline of the RBSM

The RBSM method (Kawai 1978) considers each element to be composed of many rigid bodies and discretizes the object by using springs between each element. By using a nonlinear constitutive law for the springs, the fracture behavior of the analyzed object can be modeled. Each interface was divided into several triangles that have three individual springs, one for the vertical force and two for the orthogonal tangential forces, as shown in Fig. 2 (Yamamoto et al., 2008). The bending moment on the contact surface (e.g., Fig. 2, gray colored pentagonal) was expressed by installing springs at each center of the gravity of sub-divided triangle. The behavior corresponding to the nonlinearity can be evaluated by considering the softening of the spring in the vertical and shear directions.

Since the RBSM uses discontinuous elements, the behavior of discontinuous elements such as cracks can be easily reproduced. However, since the element boundary surface is regarded as a crack surface, the generation and progress of the crack are greatly affected by the size and arrangement of element divisions. In this study, random geometry using Voronoi diagrams (Bolander and Saito 1998) was used.

The components considered were coarse aggregate, mortar, and concrete elements. In addition, the reinforcing bar (rebar) element and ITZ between the aggregate and mortar were also introduced in the model.

2.2 Constitutive laws for the mortar, aggregate, and concrete springs

Constitutive laws for the aggregate, mortar, and concrete springs based on laws presented in a reference (Yamamoto et al., 2008, 2014) were introduced. Fig. 3 shows a schematic of the constitutive laws and their equations, where $\sigma^*$ is the stress of the normal springs; $\varepsilon^*$ is the strain of the normal springs; $\varepsilon^t_\sigma$ is the strain at the tensile strength of the normal springs; $f^*_\sigma$ is the compressive strength of the normal springs; $f^t_\sigma$ is the tensile strength of the normal springs; $E^*_\sigma$ is the Young’s modulus of the normal spring; $G^*_\beta$ is the fracture energy of the normal spring; $h^*$ is the length between adjacent elements (mm); $\tau^*$ is the stress of the shear springs; $\gamma^t_\beta$ is the strain of the shear springs; $\tau^t_\beta$ is the shear strength of the shear spring; $\gamma^*_\beta$ is the shear strain at the shear strength; $\phi^*_\beta$ is the internal friction angle of the shear spring; $K^*$ is the softening slope of the shear spring; $\beta^*_\beta$ is the shear reduction factor; $c^*$ is the cohesion of the shear spring; $\beta^t_\beta$ is the shear strength of the shear spring.
\(\beta^*\) and \(\chi^*\) are constants for the shear softening slope; \(\sigma^*_f\) is a constant to determine the limit of the shear strength increase; and \(\kappa^*\) is a constant for determining \(\beta^*_f\) and \(E^*_c\). In the constitutive laws, the compression failure is not explicitly considered as shown in Fig. 3(c), and the failure of brittle materials under compression load is reproduced by compression shear failure.

As Bolander and Saito (1998) presented, the RBSM expresses a macroscopic material response through the interaction of springs assuming mechanical behavior and multiple rigid elements connected to the springs. Therefore, the physical properties obtained experimentally are not necessarily those of the springs. In this study, the physical properties of the springs were calculated by multiplying the experimentally obtained properties by the constants shown in Tables 1 and 2. The compressive strength, tensile strength, and Young’s modulus for the coarse aggregate, mortar, and concrete were taken from the experimental values of Maruyama et al. (2014) and are given in Table 3. The fracture energy of concrete and mortar is calculated by the (JSCE 2002) equation:

\[ G_f = 10 \cdot (d_{\text{max}})^{1/3} \cdot f_c^{1/3} \]  

where \(G_f\) is the fracture energy (N/mm^2), \(d_{\text{max}}\) is the maximum diameter of the aggregate (mm), and \(f_c\) is the compressive strength (N/mm^2). The fracture energy of aggregate is based on the reference (Friedman et al. 1972), and that of interfacial zone is considered as an average of those of aggregate and mortar. The signs used in Fig. 3, Tables 1, 2, and 3 correspond to each other.

### 2.3 Constitutive law for the ITZ

Figure 4 shows the constitutive laws of the ITZ between the mortar and aggregate, where the coefficients \(\alpha_{\text{ITZ}}, \beta_{\text{ITZ}}, \gamma_{\text{ITZ}},\) and \(\eta_{\text{ITZ}}\) are equal to 0.5. The ITZ has a lower strength and Young’s modulus than the mortar, properties that are important to consider for evaluating the cracking behavior of concrete. The Young’s modulus and tensile strength in the tensile region were equal to half that of the mortar values and the constitutive law of the shear springs was the same as that of the mortar. The modulus and strength in the compressive region were the average of the mortar and aggregate. Since there is a scarcity of information concerning the ITZ, the fracture energy was taken as equal to half that of the mortar; this is an approximate average between the mortar and aggregate. For the physical properties of the ITZ between the concrete and other elements, the values were averaged, weighted by their spring lengths.

### 2.4 Reinforcing bar–concrete bond model

The discrete rebar model proposed by Saito and Hikosaka (1999) is used for rebar modeling. As shown in Fig. 5, the rebar is modeled as link elements with beams between them. In this study, the adhesion slip relation is modeled through springs that correspond to the relative displacement between link elements and their corresponding Voronoi generating points. Regarding the bond–slip relation, the formulation from Suga et al.
(2001) is applied to the peak strength as:

\[
\tau = 0.4 \cdot 0.9\left(f_c^c\right)^{0.53}\left[1 - \exp\left\{-40\left(s/D\right)^{0.5}\right\}\right]
\]  

(2)

where \(f_c^c\) is the compressive strength of concrete (N/mm²), \(s\) is the slip displacement (mm), and \(D\) is the rebar diameter (mm). Compressive strength of concrete is used to calculate the adhesion although the link elements can exist in each element such as aggregate. In the present model, the reinforcing bars can go through both aggregate and mortar elements.

### 2.5 Analysis model

The analysis model was composed of aggregate, mortar, and the ITZ in the region where neutron irradiation has a significant impact on the expansion of aggregate. Hereinafter, this is called a three-phase model (mortar, aggregate and the ITZ). In the three-phase model, the area up to 350 mm from the inner surface where the effect of neutron irradiation is significant was divided into two aggregate and mortar elements. Their interface was modeled using the ITZ model, and the concrete element was introduced where that impact is negligible, as shown

![Fig. 3 Constitutive laws for the mortar, aggregate, and concrete (Yamamoto et al. 2008, 2014): (a) tensile model of the normal spring, (b) shear spring model, (c) compression model for the normal springs, (d) softening coefficient of the shear springs, (e) Mohr–Coulomb criteria for the shear spring, and (f) shear reduction coefficient. In this figure, \(E_{cm}^*\) denotes \(E_m^*\) in the case of mortar, \(E_{ca}^*\) in the case of aggregate, and \(E_{cc}^*\) in the case of concrete. For \(f_t^*, G_m^*\), \(G^*\), and \(c^*\), the same notation is applied.](image)

![Fig. 4 Constitutive law of the mortar–aggregate interface (ITZ) in (a) tension and compression and (b) shear.](image)
Table 4 Compositions of the concrete and mortar (Maruyama et al. 2014).

|            | C: Unit cement mass (kg/m³) | W: Unit water mass (kg/m³) | W/C: Water-to-cement ratio (-) |
|------------|------------------------------|----------------------------|-------------------------------|
| Concrete   | 160                          | 291                        | 0.55                          |
| Mortar     | 256                          | 468                        | 0.55                          |

Table 5 Physical properties of the rebar.

| Rebar      | Perimeter | Yield point | Area | Young’s modulus |
|------------|-----------|-------------|------|-----------------|
| SD345 D41  | 130 mm    | 345 N/mm²   | 1340 mm² | 205000 N/mm²   |

in Fig. 6. Table 4 shows the mixture proportions of the concrete and mortar used in this study, matching those used by Maruyama et al. (2014).

For the dimensions of the CBS, taking the values from the previous study (Fukuya et al. 2002; Maruyama et al. 2016), the inner radius was set to 2350 mm and the outer radius was set to 4350 mm. The CBS was sectioned with a 900 mm height and an interior angle of 12°, so that the length of width of the target member is more than 10 times of used element to observe the appropriate crack propagation. The element size was approximately 20 mm in diameter up to 350 mm from the inner surface, gradually enlarged in the radial direction to a maximum of 75 mm. The volumetric ratio of the aggregate was 35%.

Regarding the boundary conditions, only the top surface was free in deformation under the dead load of 1 MPa, while Y direction of the bottom surface is fixed, while the very small stiffness of shear spring (1/1000 of concrete shear stiffness) is applied. Side surfaces are simulated the symmetrical conditions. The inner and outer curved surfaces were free to deform. The RBSM introduces boundary conditions through attached rigid plate elements (colored portions of Fig. 7). The condition that the side plates were free in the radial direction and fixed in the circumferential should be applied, however due to the complexity of applying the cylindrical coordinate system in RBSM, the radial and the vertical free deformation of the side elements was reproduced by introducing the very small stiffness of shear springs (1/1000 of concrete shear stiffness) between side plates and elements on the side surfaces. The normal springs between side plates and rigid bodies are 10¹² times larger than those for mortar or concrete. In these ways, the symmetrical boundary conditions were appropriately introduced.

Figure 8 shows the rebar arrangement and Table 5 shows the physical properties of the rebar.
The strains such as thermal expansion strains, creep strains, irradiation-induced expansion strains described below were applied to each spring as equivalent nodal forces. The strains introduced at the aggregate-mortar interface were given an average value that takes into account the stiffness of the spring.

In response to the expansion, an equivalent nodal force was applied, and up to 200 convergence calculations were made until the sum of residual forces were less than $1.0 \times 10^{-6}$. The time series analysis was conducted for sixty years. At each step, the time step was varied so that the incremental expansion strain of the aggregate springs at the innermost edge was less than 100µ.

### 2.6 Parameters

To investigate the differences depending on thermal strain, creep, rebar, and the inner steel plate, five types of analysis were conducted for comparison, as shown in Table 6. Here, T represents thermal strain, which means that the temperature distribution is considered, and C, R, and S represent the consideration of creep behavior, rebar, and the internal steel plate (which is introduced later), respectively. In addition to the aggregate expansion due to neutron irradiation, those factors are investigated.

#### 2.6.1 Aggregate expansion

For the volumetric aggregate expansion, the temperatures from the inner surface and the neutron irradiation fluence were calculated using Eq. (3), as derived from Fig. 9 (Maruyama et al. 2016) and Eq. (4), as derived from Fig. 10 (Bruck et al. 2019). In this study, the aggregate was quartz with reference to Maruyama et al. (2016). For the irradiation fluence, a value of $6.2 \times 10^{19}$ n/cm² after sixty years of operation was used (Maruyama et al. 2017).

$$T = 2.9262 \times 10^{-15} d^5 - 1.6814 \times 10^{-11} d^4 + 3.6475 \times 10^{-9} d^3 - 3.7464 \times 10^{-6} d^2 + 2.9585 d + 64.27 \tag{3}$$

where $T$ is the temperature (°C) and $d$ is the distance from the inner surface (mm).

$$A_n = -9.0403 \times 10^{-13} d^3 + 1.1722 \times 10^{-9} d^4 - 5.9127 \times 10^{-7} d^3 + 1.4700 \times 10^{-4} d^2 - 1.8596 \times 10^{-2} d + 1.0165 \tag{4}$$

where $A_n$ is the attenuation ratio (-).

In addition, by using the temperature and neutron fluence found from the attenuation ratio, the aggregate expansion rate can be calculated (Maruyama et al. 2017) as:

$$\varepsilon(n) = 18 \times \left[1 - \exp\left(-\frac{n}{K(T)}\right)\right] \tag{5}$$

### Table 6 Factors considered in each set of calculations.

| Thermal strain | Creep | Reinforcing bars | Steel plate |
|----------------|-------|------------------|-------------|
| TCR            | ○     | ○                | ×           |
| TC             | ○     | ○                | ×           |
| TR             | ○     | ×                | ○           |
| TCRS           | ○     | ○                | ×           |
| TCS            | ○     | ○                | ×           |

### Table 7 Parameters for the compression analyses.

| Time operation | Fast neutron fluence ($\times 10^{19}$ n/cm²) | Volumetric aggregate expansion at the surface (%) |
|----------------|-----------------------------------------------|-----------------------------------------------|
| 15 years       | 1.58                                          | 0.59                                          |
| 30 years       | 3.14                                          | 2.81                                          |
| 60 years       | 6.20                                          | 10.5                                         |

Fig. 9 Temperature of the CBS. The horizontal axis is the distance from the side face of the reactor core as derived from Maruyama et al. (2016).

Fig. 10 Attenuation ratio of the neutron irradiation (Bruck et al. 2019). The reference value is $6.2 \times 10^{19}$ n/cm²/yr from Maruyama et al. (2017).
where $\varepsilon(n)$ is the volumetric aggregate expansion ratio (%) and $n$ is the neutron irradiation fluence (n/cm²) where:

$$K(T) = 3 \times 10^{-9} \times \frac{\exp(2000/298)}{\exp(2000/T)}$$

(6)

where, $K(T)$ is the neutron fluence when the expansion of aggregate attains 9%. Figure 11 shows the aggregate expansion calculated from Eqs. (3) – (6) for operation periods of fifteen years, thirty years, and sixty years. The results indicate that aggregate elements around the internal surface of the CBS expand by 10% and the expansion of the aggregate falls within 100 mm from the side face of the reactor core.

2.6.2 Thermal strain

The coefficient of linear thermal expansion of the coarse aggregate was set at 9.25 × 10⁻⁶/°C, in reference to the value of the previous study (Maruyama et al. 2014). Based on the composite law, the coefficient of linear thermal expansion of mortar was determined to be 17.18 × 10⁻⁶/°C with an aggregate ratio of 35% and a hardened cement paste ratio of 65%. The reference temperature was set as 20°C for the calculation shown in Section 3.2.1.

2.6.3 Initial load and creep

In addition to its role in shielding against neutron and gamma ray irradiation, the CBS also supports a reactor pressure vessel. Hence, in this study, a stress of 1 MPa was initially introduced as a dead load in the vertical direction. In general, CBS mainly supports the reactor pressure vessel, and calculated stress of CBS from the mass of reactor pressure vessel (Mitsubishi Heavy Industries 2020) and the size of the CBS becomes less than 1 MPa.

The formulations of JSCE (2002) were used to calculate the creep strain of the concrete and mortar, given by:

$$\varepsilon_{cp}^\prime(t, t') = [1 - \exp{-0.09(t - t')^{0.6}}] \cdot \varepsilon_{nc}$$

(7)

$$\varepsilon_{nc} = 15(C + W)^{1.5} (W/C)^{2.4} (log_{10}t)^{-0.67}$$

(8)

where $\varepsilon_{nc}$ is the basic creep strain per unit stress (× 10¹⁰ /N/mm²), $C$ is the unit cement mass (kg/m³), $W$ is the unit water mass (kg/m³), $W/C$ is the water-to-cement ratio (-), and $t$ is the time (day) at a certain step, and the times at the earlier steps are set to $t'$ (day), and the final creep strain is calculated by integrating $\varepsilon_{nc}$ calculated from the above equations. All the stress history of every springs is recorded to sum up the creep strains initiated at each calculation step.

No creep occurred between the aggregates and the creep strain of the ITZ was equal to that of the mortar. At the interface between the concrete and mortar, the creep strain was calculated from the weighted average using the length of the springs.

2.6.4 Inner steel plate

In some cases, a permanent mold or a steel liner is present on the internal surface of the CBS. If these members are attached on the surface of the CBS, then the expansion of the concrete may introduce an interaction force from the members. To evaluate this impact, the inner tube-shaped 5 mm thick steel member is considered. Assuming that the steel plate deforms elastically, the external forces were applied according to the deformation of the inner elements of CBS as:

$$p_r = \frac{E \cdot t}{R^2} \cdot \frac{1}{1 - v^2} \cdot \Delta R$$

(9)

where $p_r$ is the external pressure in the radial direction (N/mm²), $E$ is the Young’s modulus of the steel (N/mm²), $t$ is the thickness of the steel plate, $R$ is the radius (mm), $v$ is the Poisson’s ratio (-), and $\Delta R$ is the displacement in the radial direction (mm).

3. Results

Figure 12 shows the deformation for the TCR case at service periods of fifteen, thirty, and sixty years. For operation exceeding thirty years, it is confirmed that cracks are generated in the region around the internal surface of the CBS. At sixty years of operation, a peeling phenomenon, which is represented by the circular crack connections, is observed. Details of the development of cracks at the inside of the CBS are shown in Fig. 13. In this figure, cases with the neutron fluence from 2.62 to 3.66 × 10¹⁹ n/cm² at the surface of CBS are shown. The red line shows the crack locations and the thickness of the lines are indicated by three ranges of crack width: 0.1 mm - 0.2 mm, 0.2 mm - 0.3 mm, and 0.3 mm and above. As aggregates were expanded, the cracks in the circumferential direction were interconnected, developing into large cracks. Fig. 14(a) shows the crack width and direction with the aggregate expansion distribution shown in Fig. 11. The vertical axis plots the crack width on a log scale and the horizontal
axis plots the distance from the internal surface of the CBS. The minimum crack width is set to be 0.001 mm as calculated from the element diameter of 20 mm and a strain of 50 \( \mu \varepsilon \), which has no effect on the hysteresis curve. The results indicate that the circumferential cracks are most prominent and that the region in which cracks occur is within 100 mm from the inside surface, similar to the aggregate expansion. Additionally, no

Fig. 12 Deformation (×5.0) for the TCR case. Cracks occur after thirty years of operation. The closed figure of the CBS after 60 years operation is shown in Fig. 15.

Fig. 13 Crack propagation. Circumferential cracks become connected and progress.
Cracks are present on the outside of the CBS. Bruck et al. (2019) concluded that the tensile stresses that exceed the tensile strength are generated from the center of the CBS to the outer edge. Obviously, the stress distribution which is affected by crack propagation is changed as shown in Fig. 14(b), there is no tensile stress which was expected as a reactive stress of compressive stress due to aggregate expansion inside of CBS in former researches (Bruck et al. 2019; Le Pape 2015). In their calculation, the applied constitutive laws for the expansion and deterioration of concrete were homogenous and not affected by the stress field; consequently, the damage propagation is not consistent with the results of this study.

The cracking behaviors for the TCR, TC and TR at a service period of sixty years are shown in Fig. 15. No significant differences in deformation and the location of cracking can be observed between the three cases. Deformations are in the radial direction and it is observed that cracks occur around the inner surface of the CBS. Figure 16 shows the crack widths for TCR, TC and TR after sixty years of operation. Up to 100 mm from the internal surface there is little difference in the crack distribution between the TCR and TC, with rebar considered to suppress the propagation of the cracks (especially circumferential direction) due to the expansion of the aggregates. It is also confirmed that creep reduces the inner crack width of the CBS in all directions. The same tendency is confirmed by Giorla et al. (2017).

The distributions of cracks for TCRS and TCS are shown in Fig. 17. First, the cracks near the internal surface is reduced by the steel plate, as compared with Fig. 16. But there is little impact of rebars on the crack distribution near the internal surface. Only the region around the rebars (75 – 125 mm from the internal surface), slight decrease in cracks was confirmed. TCS, which does not contain rebars, has no restraints, resulting in larger crack width in the 100 to 150 mm from the internal surface rather than TCRS. There is no impact of steel plate on the depth of damaged region in the CBS.

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![Fig. 14 Crack and stress in CBS affected by aggregate expansion and crack propagation.](image-url)
Fig. 15 Deformation (×5.0) for TCR (a), TC (b) and TR (c).

Fig. 16 Crack width for TCR (a), TC (b) and TR (c).
4. Discussion

4.1 Analysis conditions

(1) Mesh size
In the present RBSM, the inside of the CBS is divided into three phases: mortar elements, aggregate elements, and the ITZ. RBSM unable to explicitly take into account the crack propagations which are affected by stress-field brought by the aggregate expansion and cylindrical shape as well as restraint by rebars. The general trend of crack propagations under such stress field thought to be qualitatively reasonable, while the crack distribution is greatly affected by element size of RBSM. To understand the impact of this modeling size, a φ100×200 mm cylindrical specimen with 20 mm elements under compression was analyzed. The results are shown in Appendix. The relationship between linear expansion of specimen and aggregate expansion is well reproduced by the RBSM. In addition, the compressive strength and Young’s modulus reduction due to aggregate expansion are also roughly consistent to the experimental results. It should be noted that larger expansion of concrete overestimate the reduction effect of aggregate expansion. Consequently, in this study, it is considered that the use of 20 mm elements in the present analysis on the CBS also provides a realistic crack behavior, especially, at the beginning of aggregate expansion, which determines the direction of crack propagation. On the other hands, the crack width in later age might be overestimated. Even though the RBSM calculation results would have such limitation, the general trend that the expansion of aggregate will not cause the tensile stress in outside of CBS and crack propagate to the half of thickness of CBS because the development of cracks in circumferential direction of CBS occur due to the stress-field-dependent crack propagation. These qualitative behaviors suggest that the effect of cracking in a CBS may not lead to structural problem over the extended operation of a nuclear power plant.

(2) Boundary conditions
While the typical CBS is cylindrical, a partially truncated model is adopted in the present study. To properly represent the boundary conditions of the sectioned model, the deformation of the sides, upper surface, and bottom surface of the model are constrained, while the inner and outer surfaces are free to deform; that is, the model is biaxially constrained. Since the observation of an actual CBS wall is challenging and this analysis is only predictive in nature, it is not possible to quantify the crack width distribution and sizing exactly; however, it has been experimentally shown that cracks occur as elements are pushed in the unrestrained direction under biaxial restraint (Liu et al. 1972; Shang and Song 2006). Thus, the findings on stress transfer and crack orientation are valid.

4.2 Differences from previous studies
The elastic analysis by Le Pape (2015) showed that a tensile stress exceeding the tensile strength occurs outside the CBS. Bruck et al. (2019) demonstrated that tensile cracking occurs from the center of a CBS to the outside of a CBS. However, some of these boundary conditions are unknown, and it is difficult to evaluate the crack propagation and degradation that is dependent on the three-dimensional stress field. Alternatively, in this analysis, the cracks around the expanding aggregate can be easily described by an examination at the material level using the RBSM, and under the constraint conditions, the cracks tend to connect and expand circumferentially so that the reaction force does not transfer to outside of the member as confirmed by Fig.14(b).

In the case of a 2D calculation, when a two-phase (aggregate–mortar or aggregate–hardened cement paste) system is modeled and assuming an aggregate expansion distribution, inter-connected cracks at the surface are possible, owing to large differences in the expansion strain of each aggregate. While it is possible to connect aggregates by cracks, this process cannot take into account the cylindrical shape of the CBS, which may introduce internal compressive stresses. Therefore, a 2D calculation results does not explain why the aggregate expansion can not produce the tensile strength at the outside of CBS appropriately.

From the difference between the presented results and
the previous results in the literature, it is suggested that a three-dimensional stress-field-dependent degradation model (e.g., the ASR model (Pietruszczak 1996; Capra and Sellier 2003)) is important to evaluate the crack propagation of concrete due to aggregate expansion.

4.3 Aging management

It is critical to evaluate the deterioration of CBS in order to predict its future soundness and to perform appropriate aging management for CBS walls in a nuclear power plant. Based on the findings of this analysis, the following countermeasures can be considered for the radiation-induced degradation of CBS.

First, the risk of cracking inside the CBS should be considered. This is because circumferential cracks form inside the member, and thus delamination progresses. If there is no permanent formwork or steel liner on the inside surface of the CBS, then the loss of shielding capability due to spalling must be considered, although, in most cases, it is assumed that some kind of material is present on this inside surface. The criteria of spalling should be investigated. In the previous experiment, the concrete after the expansion of 2% after neutron irradiation still kept their shape and compressive strength and Young’s modulus could be investigated (Maruyama et al. 2017). Therefore, the criterion of the spalling has not been clarified yet.

The possibility that reaction forces from aggregate expansion will occur inside the CBS as a result of the permanent formwork or the steel liner must also be considered. It is observed that cracks would progress up to 200 mm in the member with a 5 mm thick steel tube. However, these cracks may not affect the shielding performance (Takiguchi et al. 2009) nor structural performance as the crack size is very small.

It is clarified that cracks with a width of less than 0.01 mm appear around the rebars and it is also confirmed that the rebars plays a significant role in mitigating crack propagation in the radial and circumferential directions. The obtained value is very limited and has almost no impact on the tension stiffening behavior of the reinforced concrete. The cracks near the rebar due to aggregate expansion up to sixty years of operation do not appear to result in significant bond deterioration in the present calculations.

5. Conclusion

A three-dimensional rigid-body spring network was introduced to analyze the concrete biological shields (CBS) which is under the risk of aggregate expansion due to neutron irradiation. The analysis model was 2000 mm in thickness and consisted of coarse aggregate, mortar, interfacial transition zones, and concrete elements. The analysis factors included aggregate expansion, reinforcing bars (rebar), thermal strain, creep, and an internal steel plate that simulated a permanent formwork or an internal steel liner. Analyses were conducted for sixty years of operation. The findings are as follows:

1. The aggregate expansion due to neutron irradiation causes cracking and the cracks tend to connect and expand circumferentially so that the reaction force does not extend outside of the member, with the connection of these cracks leading to the delamination of the surface concrete.

2. It is indicated that rebars and creep suppress the growth of cracks that exceed 0.001 mm to approximately 100 – 150 mm from the inner surface. Similarly, the 5 mm thick inner steel plate causes cracks to progress up to 150 mm from the internal surface, and it was found that such inner steel plate has little influence on the damage accumulation.

3. It is suggested that a three-dimensional stress-field-dependent degradation model is necessary to evaluate the crack propagation of concrete due to expansion of aggregates.

4. Delamination behavior due to the neutron-induced expansion of aggregate may suggest the risk of the reduction of shielding performance by spalling of the surface concrete. The criteria that concrete spalling should be investigated in future. As the concrete after 2% of expansion, it still keeps their shape and cannot decay into pieces.

5. Based on the present calculations, the rebars play a role in reducing the radial and circumferential crack propagations. After sixty years of operation, the cracks around the rebars are less than 0.1 mm in size and may not have any significant impact on the bond between the concrete and rebar.

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Appendix

The physical properties of a φ100 × 200 mm cylindrical model consisting of aggregate and mortar of the same size as used for CBS was evaluated for the compression test. The constitutive laws of each spring are the same as those of the springs for the CBS. The model is shown in Fig. A1. To investigate radiation-induced changes in properties, compression analyses after aggregate expansion are carried out for the same model. The aggregate expansion which is assumed neutron fluence in this calculation is shown in Table A1.

Figure A2 shows the deformation for each compressive analysis at the compressive strength. Figure A3 shows the relationship between aggregate expansion and concrete expansion, which is compared with the previous experiments (Maruyama et al., 2017). The results showed good agreement with the experiments. Figure A4 shows the corresponding stress–strain curves. The typical stress–strain curve is confirmed. This analysis also reproduces the reduction in compressive strength due to the effect of aggregate expansion. Figures A5 and A6 show the compressive strength ratio (the ratio of compressive strength after aggregate expansion to the original compressive strength) and Young’s modulus.

### Table A1 Parameters for the compression analyses.

|          | Fast neutron fluence \((×10^{19} \text{ n/cm}^2)\) | Aggregate expansion (µ) |
|----------|-----------------------------------------------|--------------------------|
| Exp-0    | 0                                             | 0                        |
| Exp-0.75 | 0.75                                          | 1200                     |
| Exp-1.0  | 1.0                                           | 1760                     |
| Exp-1.5  | 1.5                                           | 3040                     |

Fig. A1 φ100×200 mm cylindrical model for the compression test. Displacement is given to the plate shown in red in (a).

Fig. A2 Deformation (×20) of the cylindrical models.

Fig. A3 Aggregate expansion – concrete expansion.

Fig. A4 Stress–strain curves under compressive loading.
ratio (the ratio of Young’s modulus after aggregate expansion to the original Young’s modulus) with the experimental values from previous studies.

Considering that the trends of compressive strength and Young’s modulus are similar to those of experimental results and that the compressive strength ratio and Young’s modulus ratio are qualitatively shown to be degraded due to aggregate expansion, especially in the range of smaller aggregate expansion, the use of elements of the same size in the CBS allows for an appropriate crack propagation.