- *Technical Paper* -

EFFECT OF AGGREGATE EXPANSION BY NEUTRON IRRADIATION ON CONCRETE BIOLOGICAL SHIELD WALL

Daisuke KAMBAYASHI[*1], Hiroshi SASANO [*2], Hamza SAMOUH [*3] and Ippei MARUYAMA [*4]

ABSTRACT

Concrete is used for biological shielding wall, and there are parts that are affected by radiation in the long term. Previous studies have reported that neutron irradiation causes the aggregate expansion and loss of strength and Young's modulus. Hence, it is crucial to predict the effect on the concrete biological shield (CBS) in the future. In this study, Rigid Body Spring Model (RBSM) was used to conduct a numerical analysis on CBS. As a result, it was confirmed that no tensile stress was generated on the outside of CBS, which was different from the previous analyzes by the finite element method.
Keywords: concrete biological shield, concrete, crack, RBSM

1. INTRODUCTION

Since concrete structures in nuclear power plants have high costs to rebuild them, it is essential to carry out Aging Management to evaluate the present and future soundness of structures. It is important to predict the deterioration of the material in the future.

Concrete is used for the biological shielding wall in nuclear power plants, and there are parts that are affected by radiation such as neutron rays and gamma-rays in the long term. Previous studies [1][2] have shown that neutron irradiation causes volumetric aggregate expansion and loss of concrete strength and Young's Modulus and that the irradiated material generates heat by absorbing energy. It has been experimentally confirmed that there is no deterioration due to gamma rays [2].

As a study about the effects of neutron irradiation on a concrete biological wall, Le Pape [3] used Finite Difference Method (FDM) for the expansion and loss of strength and Young's Modulus due to irradiation using a regression equation expressed by a function based on the fluence. In this study, the elements with the outer diameter of 8000 mm and the inner diameter of 4800 mm were homogeneous concrete elements without considering reinforcing bars (rebar). As a result, compressive stress 400 mm from the inner surface and tensile stress exceeding the tensile strength on the outside were observed. Bruck et al. [4] showed that the tensile stress was generated also in the vertical direction, and as a result of nonlinear analysis, tensile cracks were formed up to the center of the concrete biological shield (CBS). However, these analyzes on homogeneous elements did not consider the reduction of stress transmission due to cracks caused by aggregate expansion, it might not be an appropriate evaluation.

In this study, in order to evaluate the effects of aggregate expansion due to neutron irradiation on CBS wall including the cracking behavior of concrete, rigid spring model [5] which composed of mortar, aggregate, and interface (interfacial transition zone, ITZ) elements were applied for analysis.

2. ANALYSIS OUTLINE

2.1 RBSM

Rigid Body Spring Model (RBSM) is a method [5] considering each element composed of many rigid body individuals and discretizing the object by springs between each element. By using a nonlinear constitutive law for the springs, the fracture behavior of the analyzed object can be expressed. Each interface was divided into several triangles which have three individual springs, one for a vertical force and two for orthogonal tangential forces as shown in Fig. 1 [6]. Random geometry using Voronoi diagrams [7] was used.

2.2 Modeling of material

Regarding the constitutive law of materials, the elements were modeled as aggregate, mortar, concrete element, and ITZ.

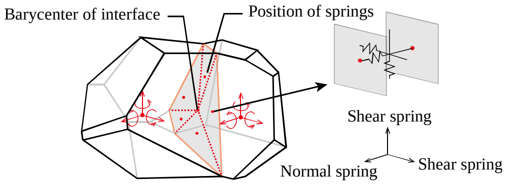
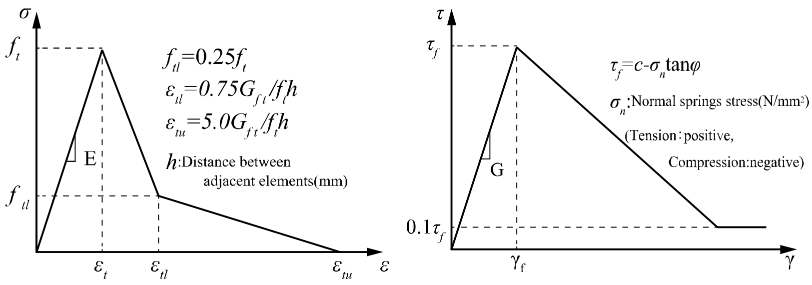


Fig.1 Schematic of the elements in RBSM and springs connection them

*1 Dept. of Architecture, Undergraduate School of Civil Engineering, Nagoya University JCI Student Member
*2 Doctoral student, Graduate School of Environment Studies, Nagoya University, JCI member
*3 Appointed Assistant Professor, Graduate School of Environment Studies, Nagoya University, JCI member
*4 Prof., Graduate School of Environment Studies, Nagoya University, JCI member



(a) Tensile model of vertical spring (b) Shear spring model normal spring

Fig. 2 Schematic of stress-strain relationships for aggregate, mortar, concrete springs

Table 1 Physical properties of materials in the numerical analysis

	Vertical Spring			
	Young's modulus	Tensile strength	Fracture energy	Compressive strength
	E (N/mm^2)	Ft (N/mm^2)	Gf (N/m)	Fc (N/mm^2)
mortar	16900	3.8	0.06	46
aggregate	70000	7.0	0.02	-
concrete	25100	3.0	0.10	51
ITZ	※1	※1	0.03	-

※1 refer to Fig.3

Table 2 Physical property of rebar

Rebar	Perimeter	Yield point	Area	Young's modulus
SD345 D41	130 mm	345 N/mm^2	1340 mm^2	205000 N/mm^2

(1) Aggregate, mortar, concrete elements

Fig. 2 shows the constitutive laws for the vertical and tangential shear springs of aggregate, mortar, and concrete elements. The mechanical properties of the materials used for aggregate, mortar and concrete elements as shown in Table 1. In this study, the fracture energy referred to the equation in the Japan Society of Civil Engineers. The tensile strength and fracture energy between aggregate elements are the same value as those of mortar. As for other values, we referred to the values of previous studies [8]. In the previous study, the physical properties of aggregate, mortar and concrete composed of them are obtained by experiments; therefore, using these values, it is able to compare the model composed of concrete with the model composed of aggregate and mortar. The tensile behavior of these elements is followed by a branch of 1/4 model based on their fracture energy. Compression behavior is modeled as a linear elastic. As for the shear spring, its behavior is defined by Mohr-Coulomb type criterion.

(2) ITZ

Fig. 3 [9] shows the constitutive law of ITZ between aggregate and mortar. where, α, β, γ: coefficient (α, β, γ=0.5). ITZ has lower strength and Young's Modulus than mortar [10], which are important to consider for evaluating the cracking behavior of concrete. In this study, we referred to the values of previous studies [9]. Young's modulus and tensile strength in the tensile

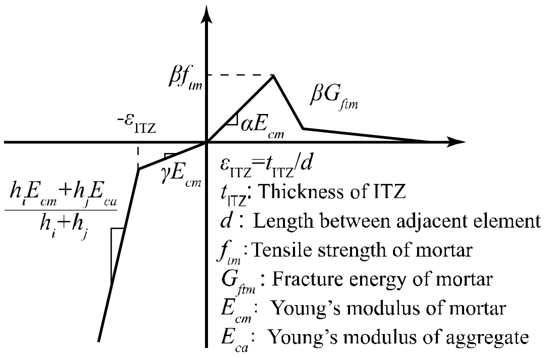


Fig.3 Constitutive law of ITZ between aggregate and mortar

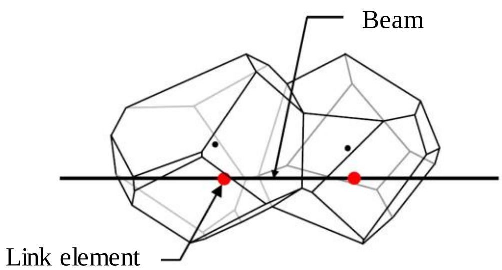


Fig.4 Discrete rebar model

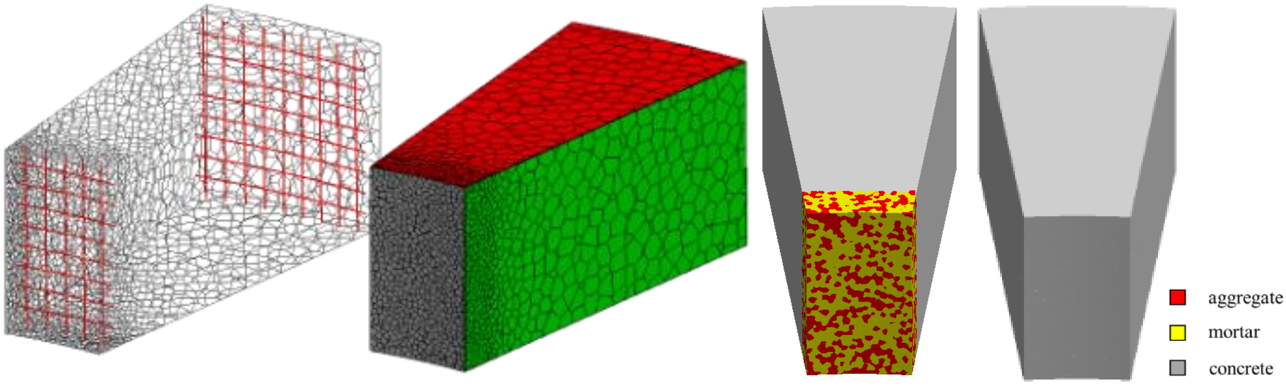


Fig.5 Analysis models

region are equal to the half of mortar values, and the constitutive law of the shear springs is the same as that of mortar. Those in the compressive region are the average of aggregate and mortar. Since there is a scarcity of information concerning the ITZ, the fracture energy was taken equal to the half of that of mortar, assuming the existence of a transition zone. For the physical property of ITZ between concrete and others, the values were weighted averaged by its spring length.

(3) Reinforcing bar (rebar)

The discrete rebar model proposed by Saito is used for rebar modeling [11]. As shown in Fig. 4, the rebar is modeled as link elements and beams between them. In this study, the adhesion slip relationship is modeled by installing springs which correspond to the relative displacement between link elements and their corresponding Voronoi generating points. Table 2 shows the physical property of rebar.

(4) Material parameters

As shown in the previous study [7], RBSM expresses macroscopic material response by the interaction of springs assuming mechanical behavior and multiple rigid elements connected the springs. Therefore, the physical property value obtained in the experiment is not necessarily that of springs. In this study, the value given in the previous study [7] is used.

3. ANALYSIS BY RBSM

3.1 Analysis models

This analysis used two models, one is composed of concrete element and another is composed of aggregate, mortar, and ITZ in the region where neutron irradiation has a large impact on the expansion of aggregate. In the latter model, the concrete element was introduced where that impact is negligible, as shown in Fig. 5 (c). Hereinafter, the former is called a concrete model and the latter is called a 3-phase model. In the 3-phase model, the area up to 200 mm from the inner surface where the effect by neutron irradiation is concerned is divided into two elements of aggregate and mortar. Their interface is modeled as the ITZ model and the outside is the concrete element.

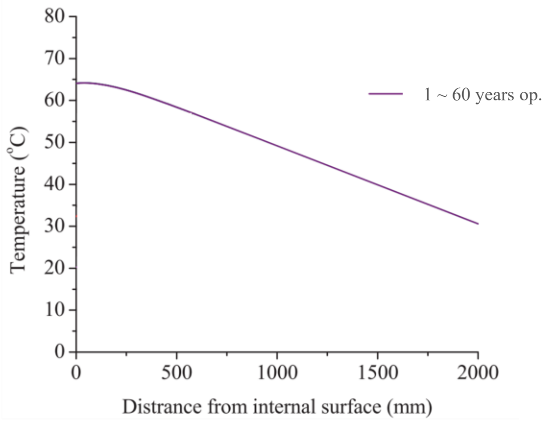


Fig. 6 Distance - Temperature [1]

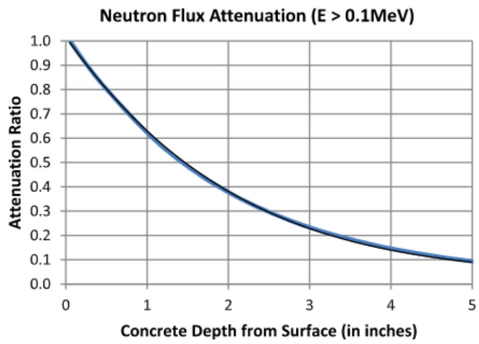


Fig.7 Distance - Irradiation attenuation ratio [4]

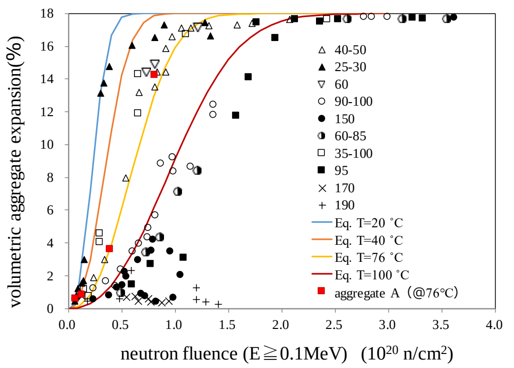


Fig.8 Irradiation amount - volumetric aggregate expansion [12]

For the dimensions of the concrete biological shield (CBS), we refer to the values of the previous study [2], and set the inner radius to 2350 mm and the outer radius to 4350 mm. The model used in this study is a cut-out part of CBS, with 900 mm height and an interior angle of 12 °. The element size is about 20 mm in diameter up to 350 mm from the inner surface, gradually enlarge in the radial direction to a maximum of 75 mm. The volumetric ratio of aggregate is 35%.

Regarding the boundary conditions, only the top surface is free to be displaced vertically, and other directions of the surface, side surfaces and the bottom surface are completely fixed. The inner and outer curved surfaces are free to deform. RBSM introduces boundary conditions by attaching plate elements (colored part in Fig. 5 (b)). In order to emulate the continuum, the shear stiffness of springs between plate elements and other elements is 1/1000 of that of concrete, simulating circumferential fix and radial free deformation.

The same analysis without reinforcing bars (rebar) was also performed for the sake of examination about structural response depending on rebar.

In response to the expansion, the equivalent nodal force was applied, and up to 200 times convergence calculations were performed until unbalanced force converged. Time series analysis was conducted for 60 years.

3.2 3-phase model's input

In calculation the volumetric aggregate expansion, temperatures from the inner surface and the neutron irradiation attenuation rate are calculated by following Eq. 1 derived from graph (Fig. 6) [1] by Maruyama et al. and Eq. 2 derived from graph (Fig. 7) [4] by Bruck et al. As a reference of the irradiation amount, we referred Mihama No. 2 values of 1.03×10^{18} n/cm^2.

$$T = (2.9262 \times 10^{-15})d^5 - (1.6814 \times 10^{-11})d^4 + (3.6475 \times 10^{-8})d^3 - (3.7464 \times 10^{-5})d^2 + (2.9585)d + 64.27 \quad (1)$$

where,

T : temperature (°C)

d : distance from inner surface (inches)

$$An = (-9.6891 \times 10^{-6})d^5 + (4.8793 \times 10^{-4})d^4 - (9.6891 \times 10^{-3})d^3 + (9.4840 \times 10^{-2})d^2 - 0.47235d + 1.0165 \quad (2)$$

where,

An : attenuation ratio (-)

In addition, from temperature and dose that is calculated from the attenuation ratio, the aggregate expansion rate is calculated by using Bykov's graph (Fig. 8) [12].

$$\varepsilon(n) = 18 \times \left(1 - exp\left(-\frac{n}{K(T)}\right)\right) \quad (3)$$

where,

$\varepsilon(n)$: volumetric aggregate expansion ratio (%)

n : neutron irradiation amount (n/cm^2)

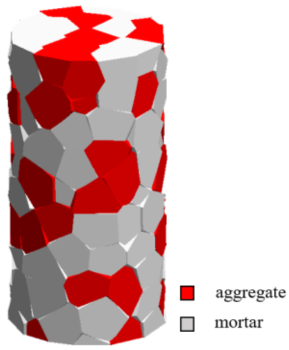


Fig.9 Cylinder model

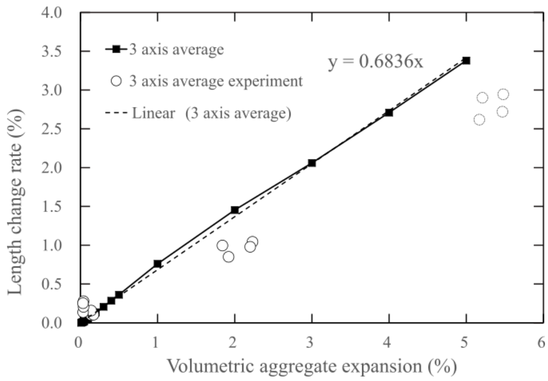


Fig.10 Volumetric aggregate expansion - length change rate

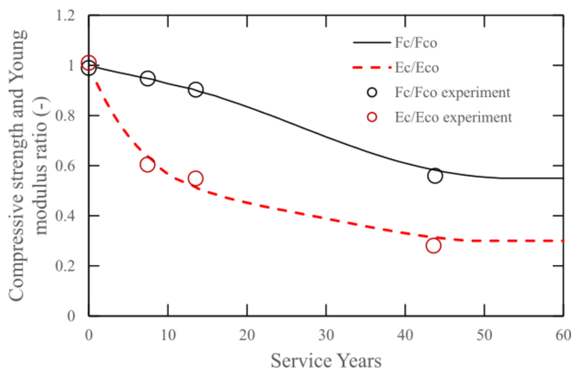


Fig.11 Service Years - Compressive strength and Young's modulus ratio

$$K(T) = 3 \times 10^{19} \times \frac{Exp(2000/298)}{Exp(2000/T)} \quad (4)$$

3.3 Concrete model's input

(1) Calculation of volumetric concrete expansion

In order to calculate the volumetric concrete expansion, the length change rate when aggregate expands was calculated by analysis in a cylinder model of φ100×200 mm, as shown in Fig. 9. Fig. 10 shows a graph plotting the volumetric aggregate expansion on the horizontal axis and length change rate on the vertical axis. The same trend of study by Maruyama et al. [2] is confirmed. Using the following linear approximation Eq. 5, volumetric concrete expansion is calculated.

$$\varepsilon_{con}(n) = 0.6836 \times \varepsilon(n) \tag{5}$$

where,

$\varepsilon_{con}(n)$: volumetric concrete expansion ratio (%)

(2) Loss of concrete strength and Young's modulus

The study by Maruyama et al. [2] confirmed that neutron irradiation reduces both compressive strength and Young's modulus of concrete. Therefore, in this study, the compressive strength and Young's modulus of concrete are reduced by the following equations (obtained from Fig. 11) referring to the experimental values by Maruyama et al. [2].

$$\begin{aligned} Fc/Fco = {} & 2.6948 \times 10^{-5} \times N^6 \\ & - 7.6306 \times 10^{-4} \times N^5 \\ & + 7.6146 \times 10^{-3} \times N^4 \\ & - 3.0191 \times 10^{-2} \times N^3 \\ & + 3.8095 \times 10^{-2} \times N^2 \\ & - 8.2488 \times 10^{-2} \times N \\ & + 1.0 \end{aligned} \tag{6}$$

where,

Fc/Fco: Compressive strength ratio (-)

N : neutron irradiation amount (1.0×10^{19} n/cm^2)

$$\begin{aligned} Ec/Eco = {} & 5.4019 \times 10^{-5} \times N^6 \\ & - 1.7207 \times 10^{-3} \times N^5 \\ & + 2.1233 \times 10^{-2} \times N^4 \\ & - 0.12884 \times N^3 \\ & + 0.41107 \times N^2 \\ & - 0.72170 \times 10^{-2} \times N \\ & + 1.0 \end{aligned} \tag{7}$$

where,

Ec/Eco: Young's Modulus ratio (-)

4. RESULT AND DISCUSSION

Fig. 12 and Fig. 13 show the vertical stress distribution of the 3-phase model and concrete model including the reinforcing bars (rebar) after 60 years. The stress was calculated from the cut-face at 450 mm in the height. It was confirmed that compressive stress except in radial direction was applied in the area within 200 mm from the inner surface and tensile stress was generated slightly from to 200mm depth to the outer surface. It is considered that the elements don't bear stress after cracking in the inner surface, resulting in high compressive stress exceeding compressive strength. This shows the same tendency as the previous studies [3][4], except that tensile stress does not exceed the tensile strength; therefore, no crack occurs in the outside. The inner elements are constrained in the circumferential and vertical directions, and are pulled radially, which causes crack and peeling. It is considered that the expansion induced stress is not easily transmitted in the radial direction after cracking occur. Hence no tensile stress is generated near the outer surface after crack and peeling.

Fig. 14 and Fig. 15 show the crack of the 3-phase model and concrete model after 60 years. In both cases, it is observed that the crack width is large near the inner surface affected by the irradiation. In the concrete model, the difference in the cracked area due to rebar can't be confirmed; however, in the 3-phase model, the cracked area is reduced from 155 mm to 100 mm from the inner surface by rebar.

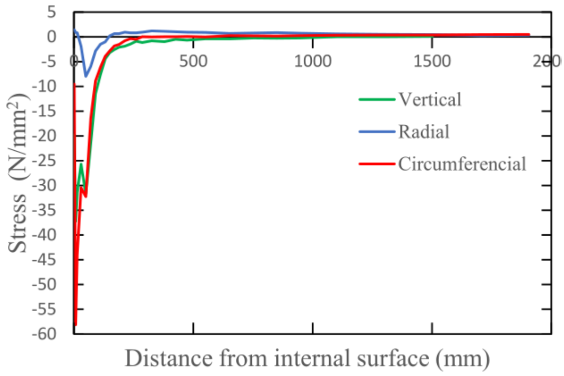


Fig.12 Stress distribution in 3-phase model

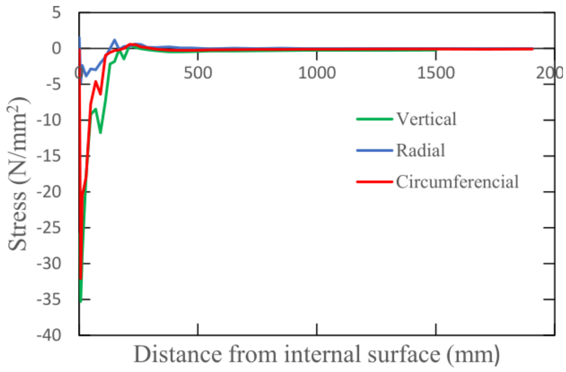


Fig.13 Stress distribution in concrete model

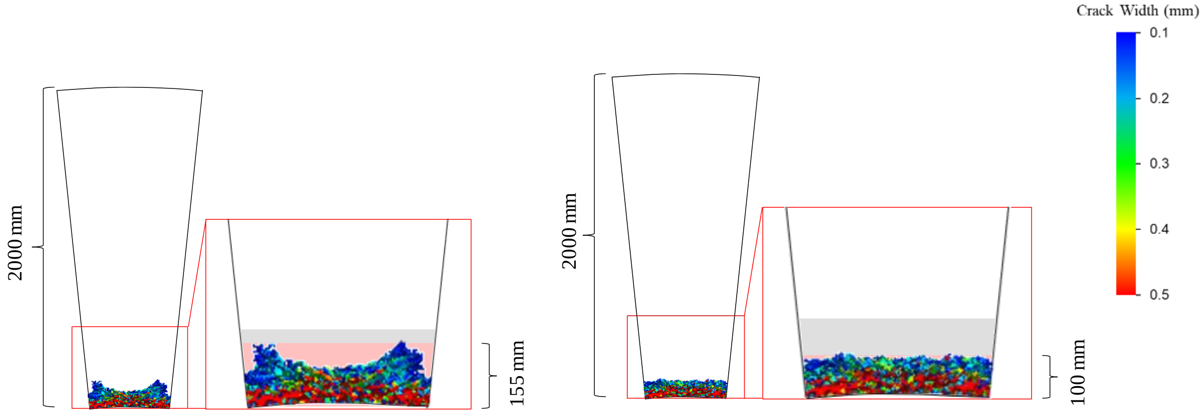
Regarding the stress distribution and crack depth, the same results were obtained for the 3-phase model and concrete model, but the crack patterns were different. This is explained by the larger inhomogeneous expansion among elements in the 3-phase model, while it is not considered n concrete model.

5. CONCLUSIONS

The purpose of this study was to investigate the cracking conditions of the concrete biological shield (CBS) affected by aggregate expansion due to neutron irradiation through the numerical analysis. A Rigid Body Spring Model (RBSM) was used for the analysis. The analysis adopted the 3-phase model consisting of aggregate, mortar, and ITZ, in addition to the concrete model. In order to examine the difference in cracking due to reinforcing bars (rebar), the same analysis was performed on a model including rebar. The findings of this study are as below:

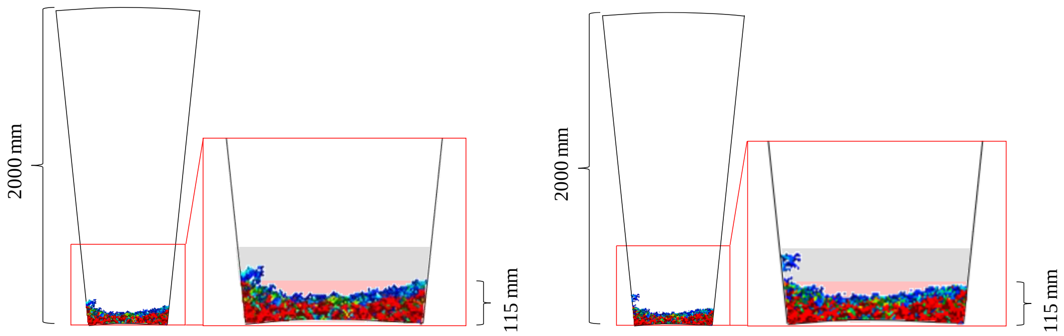
(1) It was observed that 60 years' service on CBS affected by neutron irradiation causes cracks up to 115 mm from the inner surface by the analysis.

(2) As in the previous studies [3][4], compressive stress was found near the inner surface of CBS. However, the tensile stress and tensile crack were not observed outside unlike the previous studies. This can be explained that the RBSM considered cracking and peeling on the inside; consequently, transmission of the stress from the irradiated surface (internal surface) to outer surface was reduced.



(a) without rebar (b) with rebar

Fig.14 3-phase model crack width after 60 years (6.3×10^{19} n/cm^2)



(a) without rebar (b) with rebar

Fig.15 Concrete model crack width after 60 years (6.3×10^{19} n/cm^2)

(3) In the simulation of the 3-phase model, it was confirmed that rebar reduces the crack growth, while the same degree of cracking occurred in the concrete model.

(4) Cracking behaviors were different between the 3-phase model and the concrete model, but no significant differences were observed in the stress distribution and crack depth.

ACKNOWLEDGEMENT

A part of this study was the results from the "Japan Concrete Aging Management Program on Irradiation Effects (JCAMP)" sponsored by METI in Japan.

REFERENCES

[1] Maruyama et al., "Numerical Model for Concrete Strength Change under Neutron and Gamma-Ray irradiation," Journal of Advanced Concrete Technology, Vol.14, No.4, pp.144-162, 2016

[2] Maruyama et al., "Development of Soundness Assessment Procedure for Concrete Members affected by Neutron and Gamma-Ray Irradiation," Journal of Advanced Concrete Technology, Vol.15, No.9, pp.440-523, 2017

[3] Y. Le. Pape, "Structural effects of radiation-induced volumetric expansion on reinforced concrete biological shields," Nuclear Engineering and Design, Vol.295, pp.534-548, 2015

[4] Bruck et al., "Structural assessment of radiation damage in light water power reactor concrete biological shield walls," Nuclear Engineering and Design, Vol.350, No.15, pp.9-20, 2019

[5] T.Kawai, "New discrete models and their application to seismic response analysis of structure," Nuclear Engineering and design, Vol.48, No.1, pp.297-229, 1978

[6] Y.Yamamoto, "Analysis of compression failure of concrete by three-dimensional rigid body spring model," Journal of Japan society of civil engineers, Vol. 66, pp. 48-63, 2008

[7] J.E.Bolander, S.Saito, "Fracture analysis using spring networks with random geometry, Engineering Fracture Mechanics," Vol.61, No.5-6, pp.569-591, 1998

[8] Maruyama et al., "Strength and Young’s modulus change in concrete due to long-term drying and heating up to 90°C," Cement and Concrete Research, Vol. 66, pp. 48-63, 2014.

[9] H. Sasano, I. Maruyama, "Sensitivity analysis on the impact of aggregate and ITZ strength on the concrete properties by RBSM," JCI, Vol. 41, No. 1, 2019

[10] Lyubimova , Pinus, "Interfacial Transition Zone in Concrete," 1962, pp. 51-52

[11] S.Saito, H.Hikosaka, "Numerical analysis of reinforced concrete structures using spring networks models," Proceedings of JSCE, No.627, pp.289-303, 1999

[12] Bykov, "Effect of irradiation temperature on the radiation expansion of quartz," Soviet Atomic Energy, Vol.51, No.3, pp.593-595, 1981