NUMERICAL ANALYSIS OF CONCRETE BIOLOGICAL SHIELD

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ABSTRAKT

Článek se zabývá numerickou analýzou konstrukce nacházející se kolem aktivní zóny jaderného reaktoru zajišťující biologické stínění tzv. prstenec biologického stínění. Byl vytvořen numerický model stínícího prstence pro nelineární analýzu s využitím metody konečných prvků s cílem určit dobu vzniku a následný rozvoj poškození vlivem vystavení radiaci. Jako primární zatížení byl uvažován tzv. RIVE vznikající jako důsledek neutronového záření. Výsledky se v porovnání s podobnými modely ukazují být spíše konzervativní v ohledu brzkého vzniku poškození (po 6 letech provozu). Tato skutečnost je pravděpodobně zapříčiněna zanedbáním ostatních vlivů provozu (teplota, vlhkost atp.) a dalších vlastností betonu (zejména dotvarování).

KLÍČOVÁ SLOVA

Betonový prstenec biologického stínění • Beton vystavený radiaci • Numerická analýza • Metoda konečných prvků

ABSTRACT

This study presents a numerical analysis of a structure placed around the active zone of a nuclear reactor with a biological shielding function, so-called concrete biological shield (CBS). A numerical model of the CBS was created to conduct a nonlinear analysis by finite element method aiming for determination of the time of origin and following development of damage caused by irradiation. As a primary acting load, so-called RIVE, originating from neutron irradiation, was assumed. The results indicate to be rather conservative compared to similar models in the context of damage origin (after 6 years of operation). This conclusion might be caused by neglecting other factors of reactor's operation (temperature, humidity etc) and other concrete properties (mainly creep).

KEYWORDS

Concrete biological shield • Irradiated concrete • Numerical analysis • Finite element method

1. INTRODUCTION

By the year 2022, average age of a nuclear reactor was 31 years (Schneider et al. (2022)). However, its lifespan is commonly about 30 years. Although decommission of reactors is not ecologically nor economically wise solution. Therefore, a licence of their operation is getting renewed. For such renewal, safety of the operation must be evaluated, which includes assessing structures shielding the radiation.

A concrete biological shield (CBS) is a structure with the primary goal to shield the radiation originating from nuclear fission in nuclear reactor. This structure is placed around the active zone. Basically, two types of CBS can be distinguished: a load-bearing CBS that has the shielding function as well as it presents a support for the reactor's pressure vessel and a non-load-bearing type which is purely for the shielding purposes.

This purpose leads to an important criterion, which is soundness of the structure. The soundness may be disrupted by deterioration of concrete due to the gamma or neutron irradiation. The created program aims to determine time of origin of the damage and its development during years of operation.

For this analysis, a CBS of a reactor VVER 440/213 was assumed (described in more detail in the following sections). This type is very common in European states (e.g. all reactors in NPP Dukovany are of this type) or in Russia.

2. NUMERICAL ANALYSIS

2.1. Geometry and Numerical Model of the CBS

The concrete biological shield is a structure around the active zone of a reactor. CBS of the VVER 440/213 reactor has a trapezoidal cross-section of height of 2.8 m at the highest point, the maximum thickness is 0.7 m and the inner radius is 2.37 m (see Fig. 1 or Fig. 2). As for material, the closer specification can be seen in the Table 1. The structure is placed in a steel form used as a structural framework, which is not considered in the analysis as the concrete is not fixed to the form. As for reinforcement, the structure is unreinforced.

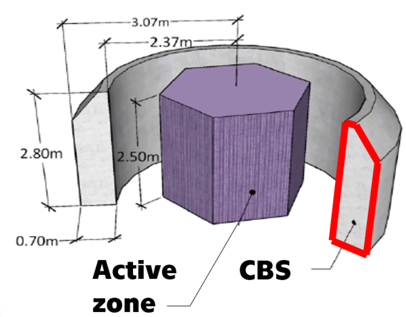

Figure 1: *Schema of the VVER 440/213 CBS in axonometry (Khmurovska et al. (2019))*

As can be seen in the Fig. 1, the CBS is a regular ring-shaped structure, therefore the assumption of an axisymmetric numerical

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model was made. Coordinates system was established as follows: r refers to radial direction, z in the vertical direction and θ in the tangential (or circumferential) direction.

Axisymmetric rigid body is defined as a three-dimensional body generated by rotating a cross-section around an axis of symmetry, resulting in consisting of the same cross-section in every point of the circumference (geometry, boundary conditions, acting load etc.). This simplification results into neglecting shear in planes perpendicular to the cross-section ($\gamma_{r\theta} = \gamma_{z\theta} = 0$) and normal stress in the tangential direction is constant ($\sigma_\theta = const$). The structure is discretized into triangular finite elements (more precisely rings with triangular cross-section in the case of axisymmetry). Both dimensions and generated mesh along with the boundary condition highlighted by the green triangle representing the steel form of the CBS being fixed to the load-bearing wall are presented in the following figure (Fig. 2).

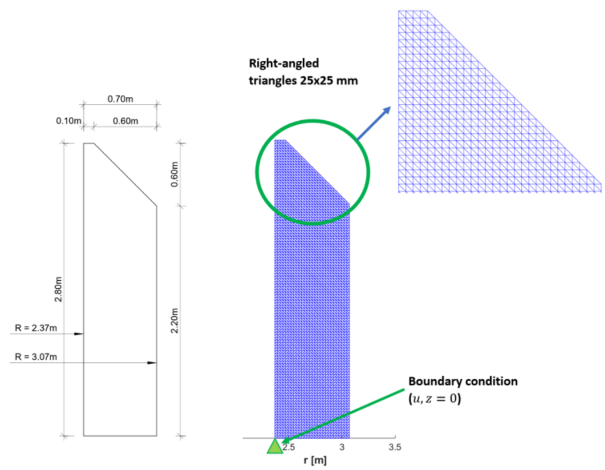


Figure 2: *Cross-section of the CBS and the considered numerical model*

2.2. Applied Load

As was stated earlier, this particular type of CBS does not provide a support for the reactor's pressure vessel, therefore, it is a self-bearing structure. In the created program, two types of load were taken into account: first, self weight and second, the phenomenon called *RIVE* (Radiation Induced Volumetric Expansion), originating from shielding the neutron radiation.

2.2.1. RIVE

The principle of shielding neutron radiation is slowing down the fast neutron with hydrogen molecules contained in the chemically bound water in the concrete. The slowed neutrons are then captured by the heavier elements - aggregates. These collisions affect the properties on the material level. In the case of irradiated concrete, the most common defect is the *interstitial defect* (Denisov et al. (2012)), which describes a situation where an atom occupies a site in the lattice in which an atom should not be. This results in expansion of the lattice and eventually, expansion of the whole material - in the context of concrete, this takes place in aggregates. Minerals, components of aggregates, expand, creating stress within the structure. As the composition of individual aggregates, naturally, varies from grain to grain, these stresses are not uniform. This mechanism is called *RIVE* and is the primary effect causing degradation of irradiated concrete (Le Pape (2015)). Following figures Fig. 3, Fig. 4 show schema of the mentioned lattice defect and the RIVE mechanism. Lastly, the two quantities describing intensity of neutron radiation: The *neutron flux*, which indicates the amount of neutrons that penetrate a cross-section of a sphere with area 1 cm^2 during 1 s and the *neutron fluence*, which is basically time integral of flux, therefore it corresponds to the total number of neutrons penetrating the cross-section (Hilsdorf et al. (1978)).

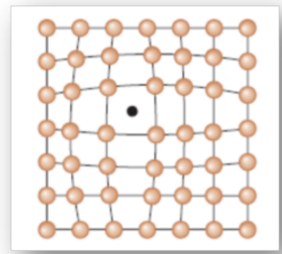


Figure 3: *Interstitial crystal lattice defect*

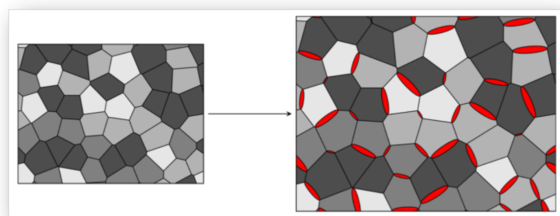


Figure 4: *Volumetric expansion of aggregates resulting in internal stresses (Le Pape et al. (2020))*

As the name suggests, it is a volumetric change, therefore it steps into the calculation in the form of homogeneous strain ε_{RIVE}, which represents expansion of the whole elements (calculated by Zubov's function modified by Le Pape (2015) as shown in Eq. 3). It is then distributed in strains in all three directions (approximated that it expands evenly by 1/3 in every direction):

$$\{\varepsilon\} = \begin{Bmatrix} \varepsilon_r \\ \varepsilon_z \\ \varepsilon_{cir} \end{Bmatrix} \tag{1}$$

$$\varepsilon_r = \varepsilon_z = \varepsilon_{cir} = \frac{1}{3}\varepsilon_{RIVE} \tag{2}$$

$$\varepsilon_{RIVE} = \kappa\varepsilon_{max}\frac{e^{\delta\Phi} - 1}{\varepsilon_{max} + \kappa e^{\delta\Phi}}, \tag{3}$$

where $\varepsilon_{r,z,cir}$ are normal strains in directions r, z and $circumferential$ respectively, ε_{RIVE} is the strain caused by RIVE, κ a fitted parameter homogeneous to strain, ε_{max} is a maximum expansion, δ stands for inverse fluence and Φ is the neutron fluence. Following values of the parameters were considered in the program to best describe the function according to Le Pape (2015): $\kappa = 0.00968$, $\varepsilon_{max} = 0.00936$, $\delta = 3.092 \cdot 10^{-20}\mathrm{cm}^2/\mathrm{n}$.

2.3. Nonlinear part of the analysis

Newton-Raphson iterative method is a widely used method for finding roots of nonlinear equations. In the created program, the modified Newton-Raphson method was implemented. The difference between these two methods lies within the usage of the stiffness matrix. Newton-Raphson method builds a new stiffness matrix in every iteration (takes the one from previous iteration and updates it based on the obtained increment Δu), while the modified method works with the initial stiffness matrix in all iterations (Kim (2014)).

Fig. 5 illustrates convergence of the method without updating the stiffness matrix. Usage of this method eventually leads to longer computational time (more iterations). To prevent divergence of the method, the maximum amount of iterations is supposed to be set. In the program, maximum of 200 iterations was set and eventually, the calculation converged in every loading step.

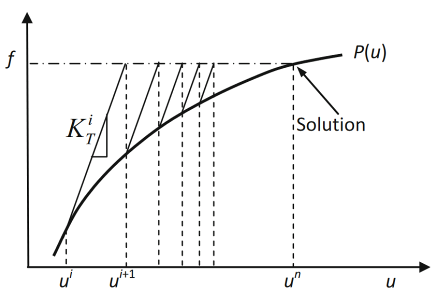


Figure 5: *Modified Newton-Raphson method (Kim (2014))*

Nonlinear behaviour occurs upon reaching a certain level of stress, mentioning concrete, this level is called *a threshold of damage*. At this point, the linear relationship between load and response (displacement, stress, strain) cannot be accounted for anymore. To describe the nonlinear behavior of concrete, the 3D Mazars' μ damage model (Mazars et al. (2015)) was considered (illustrated in Fig. 6). Primary output of the model is an isotropic value of damage that states the extent of the damage of a given finite element.

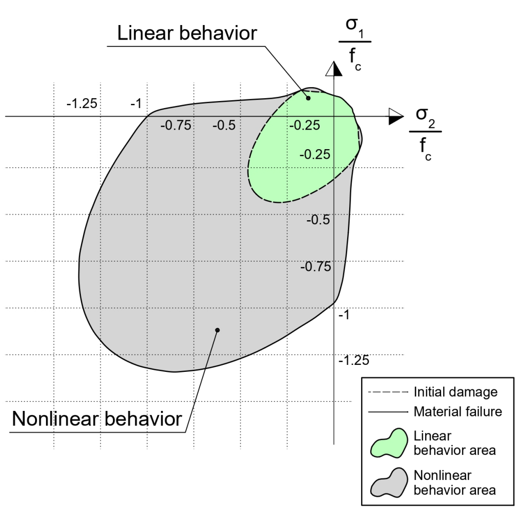


Figure 6: *Mazars' μ damage model*

The damage variable (d) states how damaged the material is and therefore how much stress it can withstand.

$$\sigma_{damaged} = (1-d)\,\sigma_i, \tag{4}$$

where d is the isotropic damage variable, σ_i denotes linear stress level of the element (given the fact that d is isotropic, it is irrelevant if the normal or principal stress is used) and $\sigma_{damaged}$ is the nonlinear stress level of the element obtained from the Mazars' model.

Following table (Table 1) summarizes material and model parameters considered in the program.

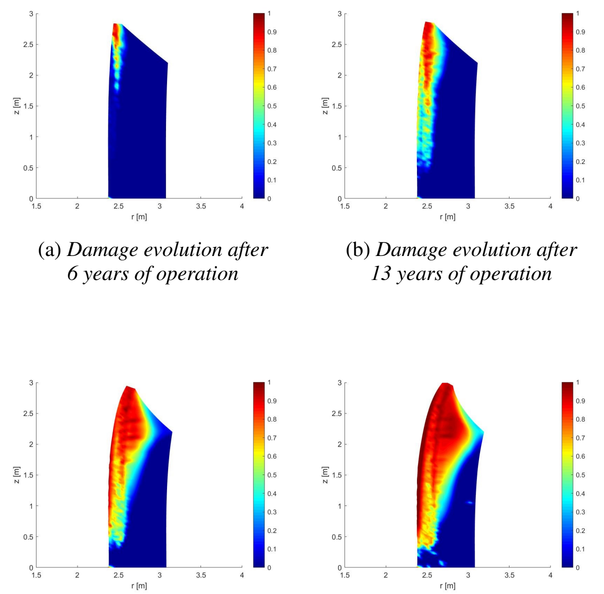
Parameter	Value	Units	Description
E	35	GPa	Young's modulus of elasticity
ν	0.2	-	Poisson's ratio
ρ	40	kN/m^3	Density
f_c	46.1	MPa	Ultimate compressive strength
f_t	3.36	MPa	Tension strength
ε_{t0}	$1.25 \cdot 10^{-4}$	-	Initial threshold of damage for ε_t
ε_{c0}	$6.85 \cdot 10^{-4}$	-	Initial threshold of damage for ε_c
A_t	0.75	-	Mazars' model parameter
A_c	1.75	-	Mazars' model parameter
B_t	17 000	-	Mazars' model parameter
B_c	105	-	Mazars' model parameter

Table 1: *Material and model parameters*

3. RESULTS AND COMPARISON WITH SIMILAR MODELS

As was stated earlier, one of the most important priorities regarding biological shield is its soundness, providing safe operation. Primary goal of the conducted analysis was to determine when the damage originates and how it develops during the years of operation. The following figures (Fig. 7) show the damage development in 6, 13, 30 and 60 years of operation.

CBS is located in an immediate vicinity of the reactor. The structure is inaccessible, making the visual assessment or a direct evaluation very problematic. Therefore, the evaluation proceeds to numerical analyses and cross-validation with same or similar models. Limited number of models on this topic is available, this chapter briefly introduces three of such models and summarizes their conclusion.



(a) *Damage evolution after 6 years of operation*

(b) *Damage evolution after 13 years of operation*

(c) *Damage evolution after 30 years of operation*

(d) *Damage evolution after 60 years of operation*

Figure 7: *Damage evolution in the cross-section of the analysed CBS*

3D RBSM analysis by Kambayashi, Maruyama et al. (2020)

The paper presented by Kambayashi et al. (2020) studies a regular cylindrical structure of a load-bearing CBS and the analysis is conducted on a 3D RBSM (Rigid Body Spring Model). The results suggest that slight damage appears after 15 years of operation and develops in the circumferential direction as can be seen in the Fig. 8. And the conclusion contradicts damage appearance on the outer surface of the structure in the opposite of the following studies (Bruck et al. (2019) or Khmurovska et al. (2019)).

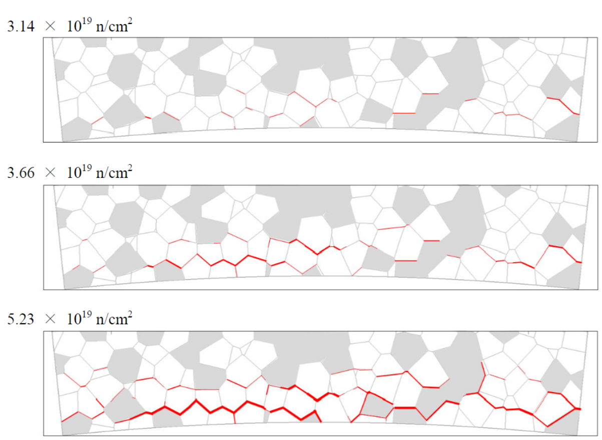


Figure 8: *Cracks development in the circumferential direction in the CBS after 15/30/60 years of operation (Kambayashi et al. (2020))*

3D FEA by Khmurovska (2019)

The results of a 3D finite element analysis by Khmurovska et al. (2019) suggest that the damage appears after 12.5 years of operation (see Fig. 9). The damage is the most severe in the upper part of the structure and the figure also shows the damage appearance on the outer surface, which agrees with Bruck et al. (2019) unlike Kambayashi et al. (2020).

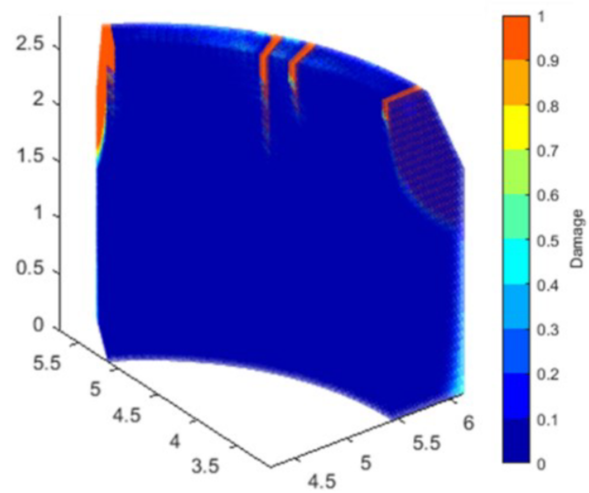


Figure 9: *Damage of the CBS after 12.5 years of operation (Khmurovska et al. (2019))*

1D analysis by Le Pape (2015)

The study by Le Pape (2015) is the oldest of the presented but is worth mentioning not just for its results but also because of the important recommendation given by the author. The results suggest damage on the outer surface (see Fig. 10) as well as Khmurovska et al. (2019) and Bruck et al. (2019) caused by the most prominent tensile stress being in the circumferential direction, which suggest the first recommendation - importance of using a 3D model to cover more aspects of reality. The author also suggests that the most important factor of irradiation is *RIVE* and needs to be accounted for in the first place along with the importance of including creep of the concrete.

The figure (Fig. 10) shows distribution of stresses in separate directions (r, z, θ), ζ indicates the distance of stress from failure criterion (ζ>1 exceeds the concrete resistance, $\zeta < 1$ stress is inside the failure criterion) and the gray area shows the resistance "zone" of the concrete.

To shortly summarize, the introduced analyses more or less agree on the damage origin after about 15 years of operation. Most of the studies also suggest the appearance of damage on the outer surface of the CBS as the reaction to the stresses on the inner surface originating from RIVE.

One more thing worth mentioning indicated by the results is that the presented model uses local approach of damage determination. However, Pijaudier-Cabot & Mazars (2001) mentions along with modification of the original Mazar's model that the nonlocal approach is an enhancement that considers sort of "distribution" of the stress among the elements adjacent to the analysed element and provides more accurate results along with reducing the mesh dependency.

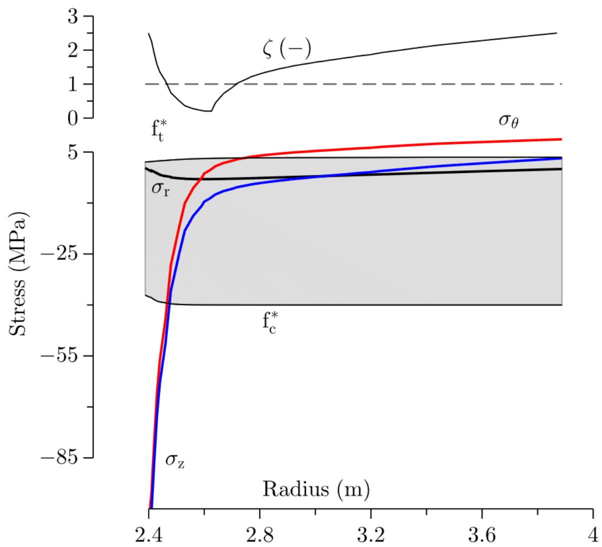


Figure 10: *Distribution of stresses over the thickness inside CBS (Le Pape (2015))*

4. CONCLUSIONS

The results, as shown in the comparison with similar analyses, seem to be rather conservative as the damage originates comparatively early (after 6 years of operation), while the other analyses conclude damage origin roughly after 15 years. The difference is not that far from the range but is non-negligible. The difference might be caused by neglecting some of the other effects either associated with radiation or concrete (mainly creep that can have a non-negligible impact on the calculated stresses in order of an analysis simulating several-years operation), which are considered in the introduced analyses. Additionally, the results indicate that while determining the damage, nonlocal approach should be used in the calculation in order to reduce mesh dependency, which show to have rather significant impact.

ACKNOWLEDGEMENTS

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References

Bruck, P., Esselman, T., Elaidi, B., Wall, J. & Wong, E. (2019), ‘Structural assessment of radiation damage in light water power reactor concrete biological shield walls’, *Nuclear Engineering and Design* **350**, 9–20.

Denisov, A., Dubrovskii, V. & Solovyov, V. (2012), ‘Radiation resistance of mineral and polymer construction materials’, *ZAO MEI Publ. House* .

Hilsdorf, H., Kropp, J. & Koch, H. (1978), ‘The effects of nuclear radiation on the mechanical properties of concrete’, *Special Publication* **55**, 223–254.

Kambayashi, D., Sasano, H., Sawada, S., Suzuki, K. & Maruyama, I. (2020), ‘Numerical analysis of a concrete biological shielding wall under neutron irradiation by 3d rbsm’, *Journal of Advanced Concrete Technology* **18**(10), 618–632.

Khmurovska, Y., Štemberk, P., Fekete, T. & Eurajoki, T. (2019), ‘Numerical analysis of VVER-440/213 concrete biological shield under normal operation’, *Nuclear Engineering and Design* **350**, 58–66.

Kim, N.-H. (2014), *Introduction to nonlinear finite element analysis*, Springer Science & Business Media.

Le Pape, Y. (2015), ‘Structural effects of radiation-induced volumetric expansion on unreinforced concrete biological shields’, *Nuclear Engineering and Design* **295**, 534–548.

Le Pape, Y., Sanahuja, J. & Alsaid, M. H. (2020), ‘Irradiation-induced damage in concrete-forming aggregates: revisiting literature data through micromechanics’, *Materials and Structures* **53**(3), 1–35.

Mazars, J., Hamon, F. & Grange, S. (2015), ‘A new 3d damage model for concrete under monotonic, cyclic and dynamic loadings’, *Materials and structures* **48**(11), 3779–3793.

Pijaudier-Cabot, G. & Mazars, J. (2001), ‘Damage models for concrete’.

Schneider, M., Froggatt, A., Hazemann, J., Katsuta, T. & Ramana, M. (2022), ‘The world nuclear industry status report 2022’, *Paris: Mycle Schneider Consulting* .