Proceedings of 23rd International Conference "MECHANIKA 2018"

Mechanical response of biological shielding ring to variations in azimuthal neutron flux distribution

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1. Introduction

According to The World Nuclear Industry Status Report [1] the unit-weighted average age of the world operating nuclear reactor is rising continuously, and by mid-2017 stood at 29.3 years (see Fig. 1), up from 29.0 a year ago and 28.8 two years ago [2]. Despite the fact that the initial design operating period of nuclear power plants is 30 to 40 years, over a half of the total 234 units have operated for 31 years and more, including 64 that have run for 41 years and more (see Fig. 1). This means that the nuclear power plants which are nearing the end of their licensed operating period need to be either shut down or their operation time licenses have to be prolonged. If all currently operating reactors were shut down by the end of their 40-year design service lifetime, by the end of 2030 some 163 reactor worldwide would have to be shut down and 144.5 GW power would have to be generated by other energy sources. It should be noted that the license renewal is rather preferable before the reactor shutdown because of the long nuclear power plant decommissioning process which is also associated with significant costs.

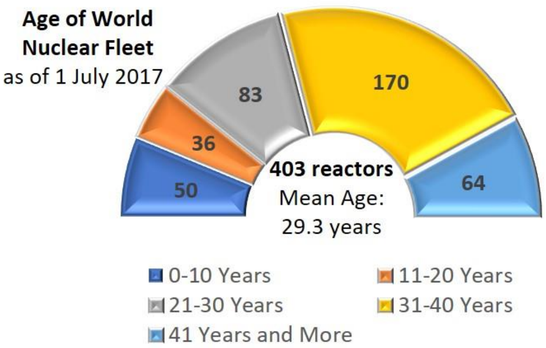

Fig. 1 Age distribution of world operating reactors [1]

The United States reactors are among the oldest in the world. With only one new reactor started up in the last 20 years, the U.S. reactor fleet average age increases up to 37.1 years by a mid-2017, among which 40 reactors have been operated for more than 40 years (Fig. 2). The United States reactors are initially licensed to operate for 40 years, but nuclear operators can apply for a license renewal for an additional 20 years from the Nuclear Regulatory Commission (NRC). As of 1 July 2017, 84 of the 99 operating U.S. units had received a license extension with a further nine applications under review. In December 2015, the NRC published a draft document about "aging management programs" that might allow the NRC to extend nuclear power plants operation life licenses for "up to 80 years". Any precedent that can confirm safety of these actions does not currently exist yet. Therefore, the development of a numerical model capable of reasonable estimation of reactor structural element behavior under long-term exposure to radiation is of particular importance.

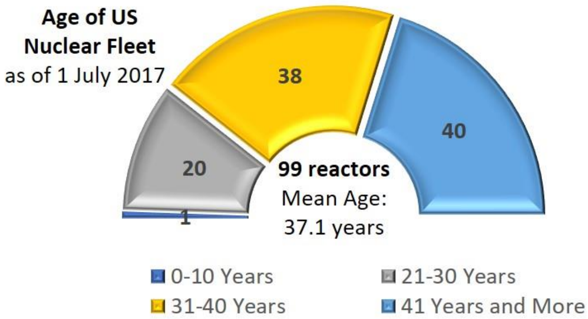

Fig. 2 Age distribution of U.S. nuclear fleet [1]

The research presented in this paper is motivated by two important facts. Firstly, the safety of concrete structures in nuclear facilities can be analyzed only numerically as there is no possibility to investigate experimentally the effect of radiation on real-scale concrete structures. The strategy is then to investigate experimentally the effect of radiation on small concrete specimens in test reactors and then to upscale numerically the obtained mechanical parameters to the real-size structural response.

Secondly, the available experimental data can be divided into two groups when the older data come from the design era of the existing nuclear power plants from the 50s thru 70s of the last century, and the latest data, which are necessary for the relicensing process. However, both groups of data contain either excessive uncertainty in definition of the experimental conditions and measurements or too few valid measurements in order to derive a relevant trend of investigated parameters.

Therefore, the goal of this study is to show an example of numerical analysis of the possible mechanical response of the concrete ring when exposed to neutron flux. Since this is one of the first papers on this phenomenon and since the ambition of this paper is not to become a platform for decisions within the relicensing processes, the numerical example of the mechanical response in terms of damage and principal stresses, which is presented in this paper, is rather theoretical. The geometry of the ring corresponds to the shape of the biological shield and the magnitude of the neutron flux corresponds to that of a typical 1000 MW PWR nuclear reactor.

2. Available resources

The properties of concrete do change under exposure to neutron flux according to the current research [3-9]. The volume of aggregates increases with dependence on the minerals chemical composition and their proportion within the aggregates. Since the distribution of the aggregates within concrete is random, the swelling causes cracks in concrete which in turn decrease its stiffness and strength.

The radiation-induced volumetric expansion is given as a function of neutron fluence (see Fig. 3) that was constructed based on the data available in [3], where the grey area indicates the scatter of experimental data and the red dashed curve indicates the average trend that is used in the analysis, the purple line indicates the neutron fluence that is representative for the biological shielding of a 1000 MW PWR nuclear reactor after the sixty years of operation. The indicated neutron fluence corresponds to $1.85\text{x}10^{10}$ $n/cm^2/s$ neutron flux, this value was obtain based on the on-site measurements of the neutron flux in the hot spot of the face of the biological shield of VVER-1000 reactor. The neutron fluence accumulated at a given year is obtained as a sum of the neutron flux when it is assumed that the reactor is active 300 full days per year.

Figs. 4-6 indicate in the same manner the trend of decrease of the modulus of elasticity, the compressive strength and the tensile strength, respectively, as relative to their initial reference values with respect to the neutron fluence. The curves in Figs. 4-6 were obtained by fitting the function to the relevant available data in [3].

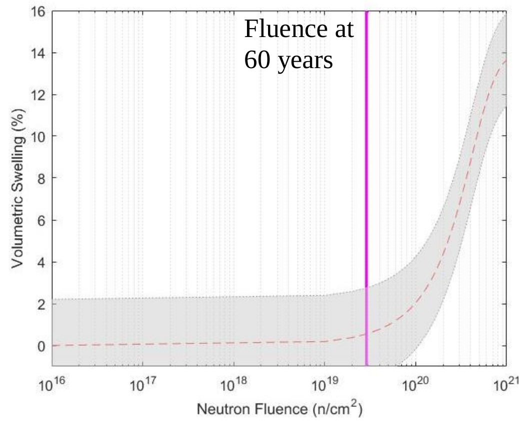

Fig. 3 Volumetric swelling of concrete versus neutron fluence

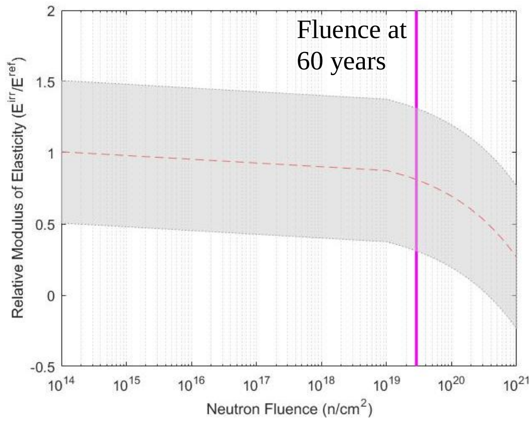

Fig. 4 Relative elastic modulus of concrete versus neutron fluence

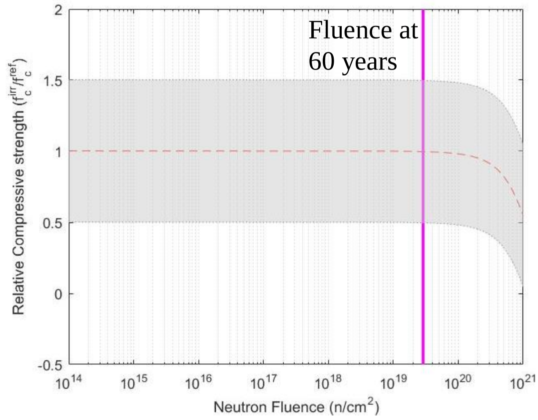

Fig. 5 Relative compressive strength of concrete versus neutron fluence

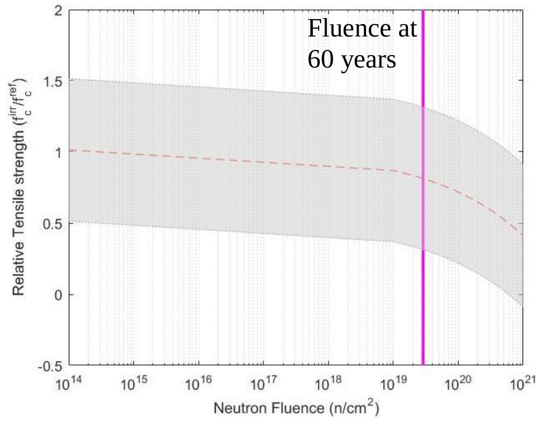

Fig. 6 Relative tensile strength of concrete versus neutron fluence

The neutron flux distribution through the shielding ring is decreasing exponentially due to attenuation (Fig. 7) and is defined:

$$k_1(d) = e^{-0.191\, d}, \tag{1}$$

where $k_1(d)$ is the reduction coefficient at given depth under the concrete surface, and d is the depth under the wall surface in cm (see Fig. 7).

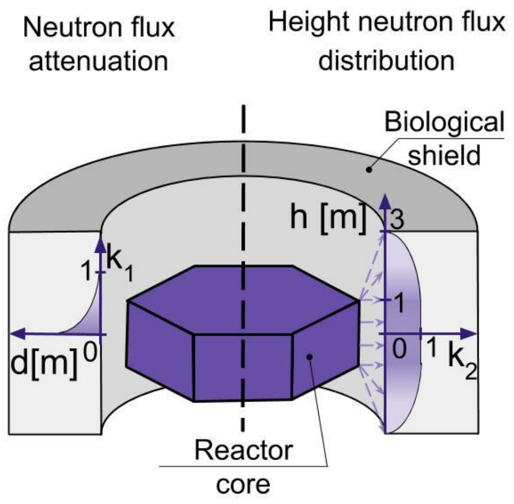

Fig. 7 Attenuation and height of neutron flux distribution

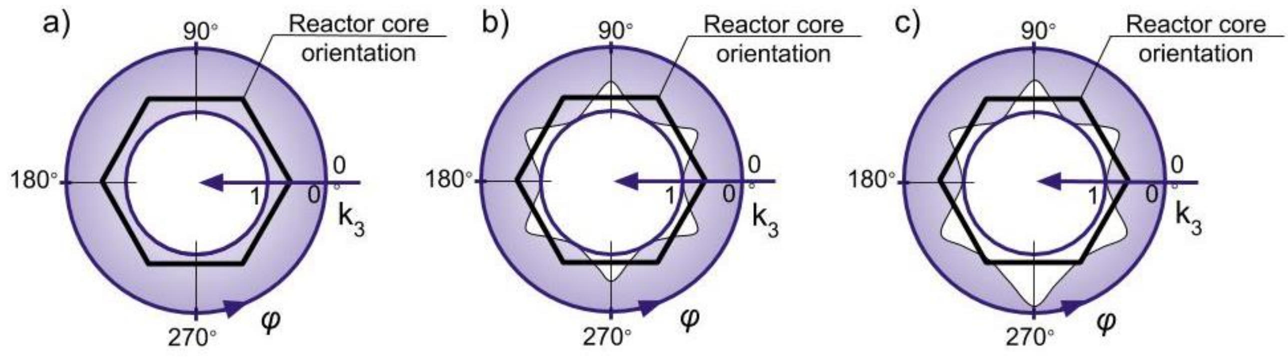

Fig. 8 Azimuthal neutron flux distribution: a – constant, b – sinusoidal, c – irregular

Since the radiation source has a special geometry, the distribution of the neutron flux is nonhomogeneous over the entire surface of the wall [9-12]. The height distribution is assumed to be of the parabolic shape with a nearly uniform distribution in the area closest to the active zone, which is considered as a strip with the height of 2 meters (Fig. 7). The parabolic reduction, which takes its effect on the annulus area defined by the inner height of 1 m and the outer height of 3 m measured from the center of the active zone (Fig. 7), is expressed:

$$k_2(h) = \frac{1}{8}\left(9 - h^2\right), \tag{2}$$

where $k_2(h)$ is the reduction coefficient and h is the height in m measured from the center of the active zone.

The azimuthal neutron flux distribution is non-uniform because of the shape of the reactor active zone, the distance between the biological shield and the reactor core and the arrangement of the fuel assemblies. In order to estimate the effect of azimuthal neutron flux distribution on the structure three cases are considered (see Fig. 8). The first case takes into account uniform azimuthal neutral flux distribution, with the constant redaction factor $k_3(\varphi)$=1 (see Fig. 8 a), that means that the maximum possible azimuthal neutron flux is considered all over the volume of the analyzed ring. The second case is related to 60-degrees symmetry of the azimuthal flux distribution due to the geometry of the reactor active zone and the biological shield [10-11] and the distance between them. Therefore, in this case the reduction factor $k_3(\varphi)$ varies according to the sinusoidal law as shown in Fig. 8 b.

The third case takes into account not only the geometry of the structure but also the possible imperfection due to fuel assemblies arrangement and uneven radial neutron flux distribution associated with it [12]. The reduction factor $k_3(\varphi)$ varies irregularly with the 180-degrees symmetry as shown in Fig. 8 c.

The total resulting flux at any point of the analyzed concrete ring is defined:

$$f = f_{surf} \cdot k_1(d) \cdot k_2(h) \cdot k_3(\varphi), \tag{3}$$

where f is the resulting neutron flux at any point of biological shield, f_{surf} is the neutron flux at the surface of the wall and assumes the value of $1.85\text{x}10^{10}$ n/cm^2/s.

Thus, a neutron fluence and corresponding changes in the properties of each material point of the numerical model can be obtained.

3. Numerical analysis

In order to clarify the understanding of the radiation-induced volumetric expansion of aggregates influence on the concrete ring performance, a nonlinear finite element analysis was performed in Matlab. A concrete ring with the inner radius of 5.77 m, the outer radius of 7.27 m, the thickness of 1.5 m and the height of 6 m was considered as shown in Fig. 9.

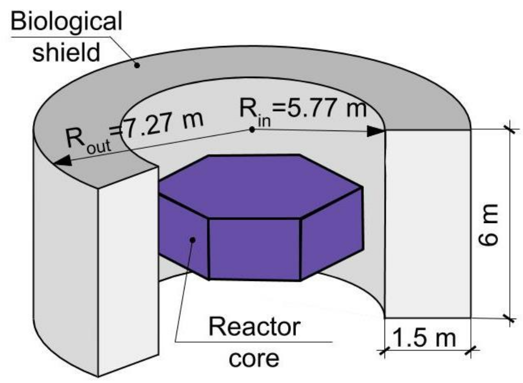

Fig. 9 Geometry of analyzed concrete ring

The analyzed structure was assumed to be made of concrete with the initial compressive strength, f_c, of 40 MPa, the initial tensile strength, f_t, of 5 MPa, the initial modulus of elasticity, E, of 35 GPa, Poisson's ratio of 0.2 and the density of 2500 kg/m^3.

The concrete ring was represented by the 12-degree-of-freedom linear tetrahedrons in this analysis. The finite element mesh is shown in Fig. 10. The applied boundary conditions are depicted in Fig. 11.

Fig. 10 Finite element mesh with boundary conditions

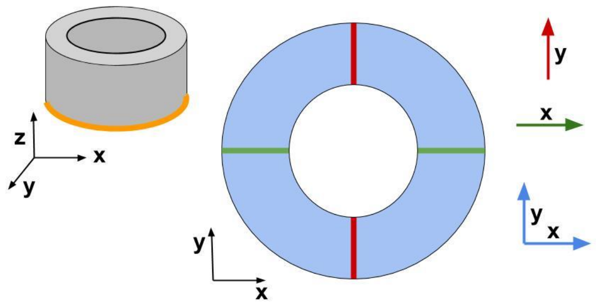

Fig. 11 Applied boundary conditions

The ring was subjected to neutron irradiation with the distribution of the neutron flux as shown in Figs. 7-8 and as defined with Eqs. (1)-(3). Three cases of the possible azimuthal flux distribution were considered (see Fig. 8). The radiation-induced volumetric expansion of aggregates that depends on the neutron fluence (see Fig. 3) is applied as the load in the presented numerical investigation. The self-weigh of the structure is also taken into account. All other possible loads are neglected due to their insignificant influence.

The nonlinear plastic analysis of concrete was performed upon reaching the limit of proportionality by mechanical damage calculation using the "μ damage model", [13], which is based on Mazars' damage model, [14]. Mazars' damage model can be used in the neutron flux damage analysis according to [15]. The damage initiation surface of Mazars' damage model and the μ-damage model are shown in Fig. 12. The tensile and compression strength of concrete varies with respect to neutron fluence as shown in Figs 5 and 6. The elastic modulus degradation due to the long-term exposure of radiation can be considered as an isotropic damage that is caused by the neutron flux. The total damage is obtained as the product of the mechanical and the radiation damage.

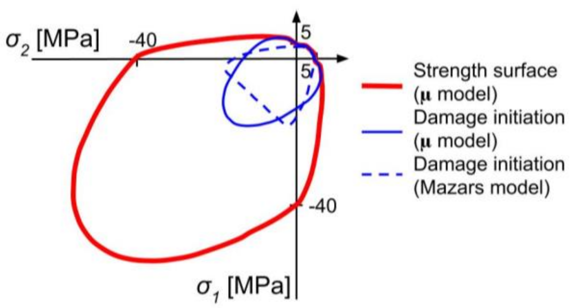

Fig. 12 Comparison of Mazars and μ-damage model in the plane σ_3=0

4. Results and discussion

The degree of damage caused by the neutron flux assessment is important for the two following reasons. First, the damage to concrete may cause biological shield displacements, which may shift the reactor vessel supports and provoke non-uniform loading conditions or, secondly, it may reduce the clearance between the reactor vessel and the biological shield surface which may prohibit the regular nondestructive integrity tests of the reactor vessel. Also, the cracks that may appear due to biological shield geometrical changes can affect the shielding properties. Therefore, the obtained results are in terms of the overall deformation and the distribution of the isotropic damage and the principal tensile stresses. These results provide some information about the location and intensity of occurrence of the possible cracks within the analyzed concrete ring. For an immediate comparison, the results are shown in parallel for the three cases of the uniform, sinusoidal and irregular azimuthal neutron flux distribution.

The displacement of the ring that was calculated linearly is depicted in Fig. 13 and shows that the change in the azimuthal flux distribution affects the analyzed structure. In all cases, the structure tends to move in the direction of the reactor core. The intensity of the displacement and their distribution varies in different cases.

The isotropic damage distribution on the concrete ring surface and its cross-section are shown in Fig. 14. According to the obtained results the azimuthal neutron flux distribution plays an important role in the analyzed structure performance. About 25% of the ring thickness is damaged in the case of the uniform azimuthal flux distribution (see Fig. 14 a). The sinusoidal azimuthal flux distribution causes even higher damage (from 25 to 50% of the ring thickness), the damage distribution basically copies the azimuthal flux distribution (see Fig. 14 b). The irregular azimuthal flux distribution damages the wall completely in the location with the smallest flux, which means the least compressed part, (see Fig. 14 c) despite the fact that the total neutron flux is lower than in other cases. Therefore, it is necessary to provide a uniform or close to the uniform azimuthal fluence distribution during the operation time of the reactor.

The distribution of the nodal principal tensile stresses of the non-destroyed elements is shown in Fig. 15. High tensile stress under the totally damage zone indicates that the movement of the zone compressed due to the volumetric expansion causes tension in the body of the structure, which can provoke cracking with subsequent segments buckling and delamination.

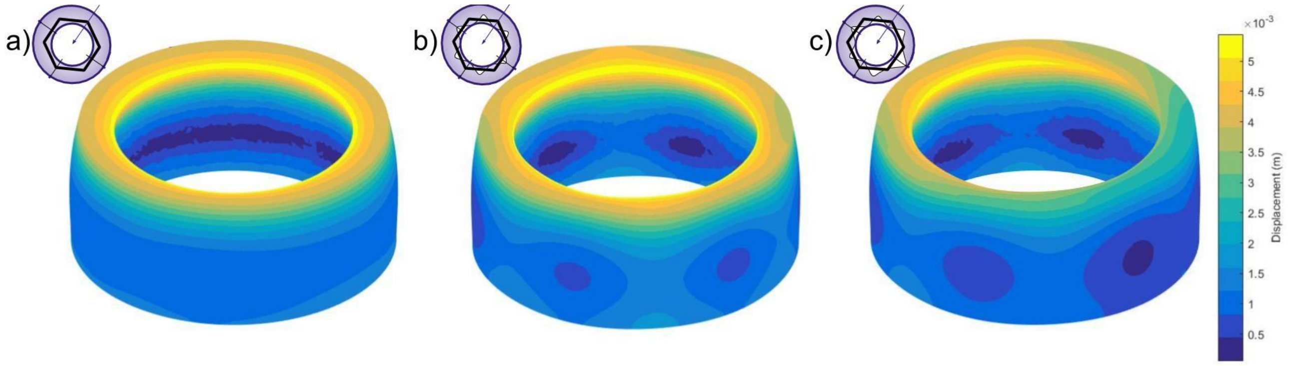

Fig. 13 Linear displacement of concrete ring: a – constant, b – sinusoidal, c – irregular neutron flux distribution

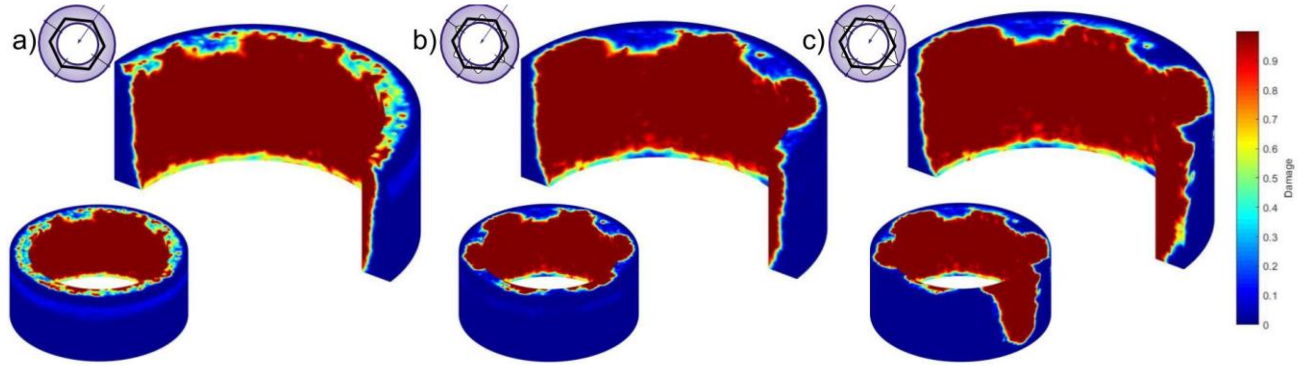

Fig. 14 Damage of concrete ring and its sectional view: a – constant, b – sinusoidal, c – irregular neutron flux distribution

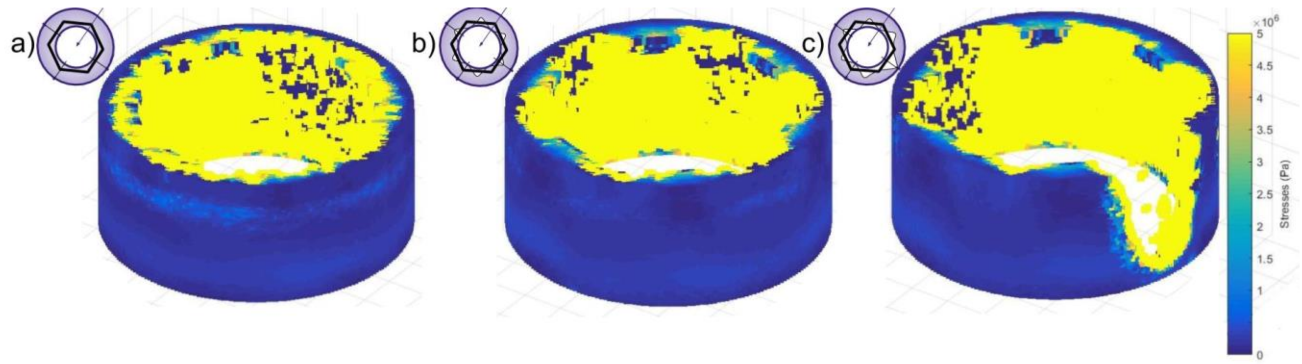

Fig. 15 Nodal principal tensile stresses in concrete ring: a – constant, b – sinusoidal, c – irregular neutron flux distribution

Two important effects need to be added into consideration when a real-life reactor biological shield is analyzed. Firstly, the time-depended relaxation effect, which can reduce the stresses significantly. The available data regarding the relaxation or creep under exposure to neutron flux are very limited and uncertain. Therefore, research in this field should be continued. Secondary, the radiation shielding is accompanied with heating of the shielding material. Similarly as in the case of the spent fuel storage casks, the effect of elevated temperature should be also considered, which would worsen the situation in the presented analysis.

The reinforcement and related effects should be also taken into account. The neutron flux has an influence on the steel reinforcement, besides the corrosive effect of the commonly encountered environment. It is expected that the bond between concrete and steel reinforcement may deteriorate similarly as in the case of humidity induced corrosion, however, no relevant experimental data, which would confirm this hypothesis, exist.

4. Conclusions

Based on the obtained results, the following conclusions can be drawn and suggestions for future work may be offered:

The prolonged exposure of concrete to radiation affects significantly the concrete properties and consequently it influences the structural and shielding performance of the reactor shaft concrete structures. Therefore, the effect of neutron flux on concrete cannot be neglected.

It is recommended to analyze the effect of neutron flux on the concrete ring as a three-dimensional problem, as important effects may be overlooked or misinterpreted when less dimensional approaches are adopted.

The azimuthal flux distribution affects the results significantly, when the irregular load can cause much higher damage in comparison to the uniform load. Therefore, the arrangement of the fuel assemblies should be optimized not only with the objective to maximize the electric output but also to minimize the detrimental effect of the neutron flux on the biological shield structural elements.

The regular inspections of reactors biological shield should be carried out after reaching the operating age of forty years in order to identify possible geometrical deviations.

The effect of stress relaxation is neglected in this study and has to be added in the future. Relaxation can reduce significantly the stresses and the corresponding damage.

Heating, which is associated with irradiation, is also neglected and has to be taken into consideration in future studies. The temperature expansion of the structural material caused by elevated temperature has to be added to the radiation-induced volumetric expansion.

In this paper, the reinforcement is not considered, but it is expectable that a local change of stiffness of the reinforced concrete structure can give a result that is different from the result obtained in this study.

To sum up, the presented analysis showed the complexity of this important problem and serves as an evidence that research in this area should be continued.

Acknowledgements

This work was supported by the Czech Technical University in Prague, project SGS18/041/OHK1/1T/11 and Ministry of Education, Youth and Sports of Czech Republic, project 8F17002, which are gratefully acknowledged. This work was part of the project No. 127102 that has been implemented with the support provided from the National Research, Development and Innovation Fund of Hungary, financed under the NN_17 V4-Korea funding scheme which is gratefully acknowledged.

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Mechanical response of biological shielding ring to variations in azimuthal neutron flux distribution

S u m m a r y

In this paper, the mechanical response of concrete ring to prolonged exposure to neutron irradiation is investigated. A three-dimensional finite element model of the concrete ring has been created. The radiation effect, represented by neutron flux, is modeled by volumetric swelling of aggregates and degradation of the mechanical parameters of concrete, based on latest literature review. Three different cases of the azimuthal flux distribution (uniform, sinusoidal and irregular) have been considered in order to investigate its effect on the analyzed structural element. The nonlinear plastic behavior of concrete is defined by the "μ damage model". As a result, displacement, isotropic damage and principal tensile stresses are obtained. According to the results of the analysis, the azimuthal distribution affects strongly the structural performance of the concrete ring. Its shielding and load-bearing properties under exposure to irregular azimuthal flux distribution may be compromised, while the structural response to the uniform azimuthal flux distribution is more acceptable. The results of the analysis are discussed in detail and the neglected factors, both positive and negative, are described. The presented analysis shows the complexity of this important problem and demonstrates the necessity for the research in this area to be continued.

Keywords: damage, elastic modulus degradation, finite element method, neutron fluence, non-linear analysis, reinforced concrete, volumetric swelling.