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# NEUTRON RADIATION EFFECT ON CONCRETE MESOSCALE SAMPLES AND CONCRETE STRUCTURES

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## ABSTRACT

Nuclear power plants' need to extend the service life of facilities raises the question of the current state of concrete structures. The main goal of this paper is to present the ability of numerical modelling of reinforced concrete structures to capture the main deteriorating effect of neutron radiation on concrete material properties, which is radiation-induced volumetric expansion (RIVE) of aggregate. Firstly, the mesoscale samples representing actual experiment, Kelly (1969), are modelled, and the comparison with actual experimental results shows good correlation. Secondly, the RIVE impact on the performance of the actual biological shield is studied assuming the maximal RIVE of concrete samples reported in literature, Field et al. (2015).

## INTRODUCTION

In last few decades, there have been a lot of nuclear facilities approaching the end of their designed service life. Often, the solution is an extension of service life depending on the condition of the facility and equipment in it. The focus of this study is on part of a nuclear power plant called biological shielding that is exposed to the highest doses of irradiation during the facility's service life because it envelopes the nuclear reactor and protects the environment around the source of radiation. The protection is not necessarily the sole purpose of biological shielding as it can serve as a load-bearing structure of the reactor as well. Therefore, the soundness of the structure is of the highest importance regarding the safe operation of the reactor.

Biological shielding is a structure made of concrete. The effect of irradiation on concrete has been investigated in 1960's and 1970's by researchers worldwide, such as Elleuch et al. (1970), Hilsdorf et al. (1978), Kelly (1969). These efforts have shown major changes in the mechanical properties of concrete caused by neutron radiation. Specifically, doses of neutrons above $10^{19}$ n/cm$^2$ result in a significant decrease of tensile and compressive strength, and modulus of elasticity. Figures 1-3 show the collection of data that compare pre and post-irradiation properties dependent on neutron fluence with the trendline presented in Filed et al. (2015). The main contributor to these detrimental effects is the radiation-induced volumetric expansion of aggregates (RIVE). Some types of aggregates are more susceptible to neutron radiation than others. That would be one of the reasons why the data on irradiated concrete show large scatter since the composition of concrete can vary not just in terms of aggregate type but also cement type. Other sources of scatter are different testing conditions such as temperature, shape and size of specimen.

In the following study, the effect of irradiation on concrete samples is introduced based on the literature data that are applied in simulations in ATENA software (Červenka V. et al. 2025). It is a finite element method-based (FEM) tool with nonlinear materials developed especially for modelling of concrete structures. The mesoscale models of actual experiments are simulated to investigate the ability of the software to capture experimental results. Once the verification of the method is shown, the structure of biological shielding can be studied regarding the effects of radiation after decades of reactor operation. Such a tool can predict potential problems or assess the extent of damage to the structure, which would support the relicensing process.

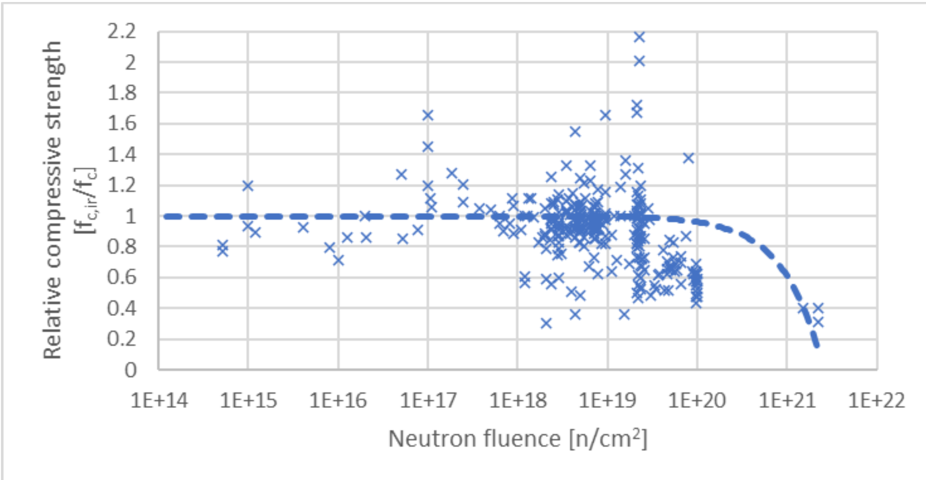


Figure 1. Relative compressive strength dependent on neutron fluence, each point represents an experimental result with the dashed line showing the trend.

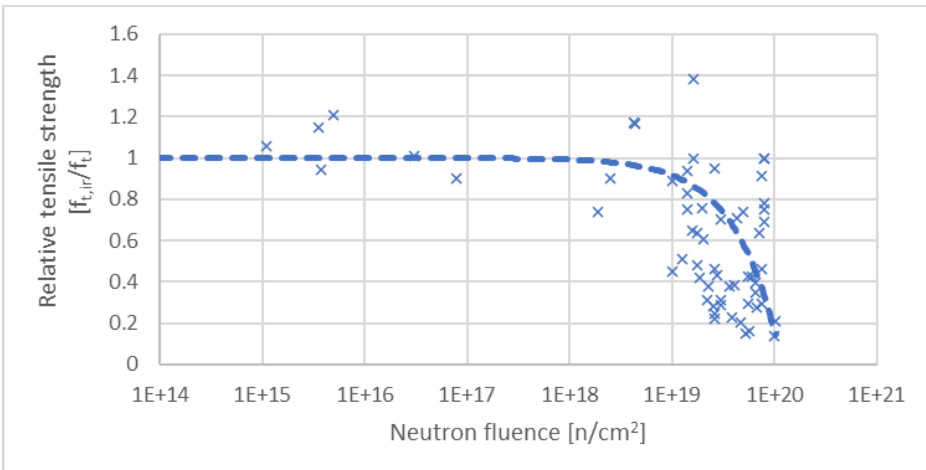


Figure 2. Relative tensile strength dependent on neutron fluence, each point represents an experimental result with the dashed line showing the trend.

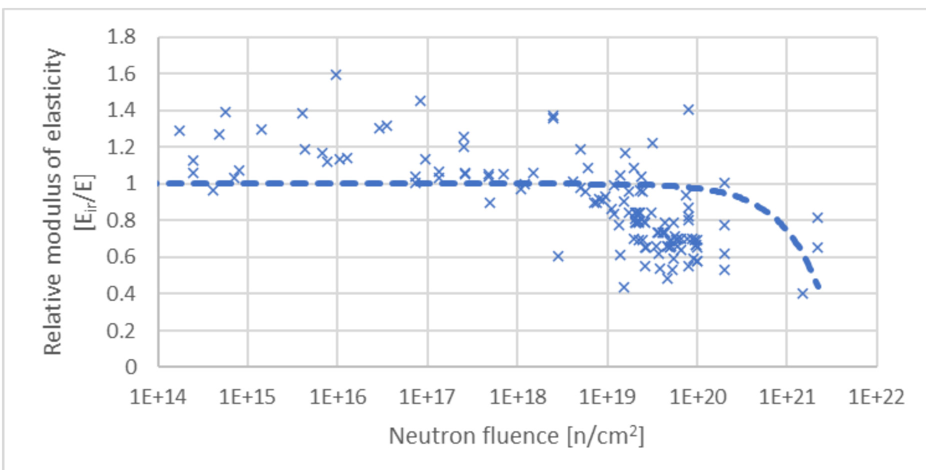


Figure 3. Relative elastic modulus dependent on neutron fluence, each point represents an experimental result with the dashed line showing the trend.

## EFFECT OF IRRADIATION ON AGGREGATES AND CONCRETE

Aggregates are the main component of concrete, filling about 60-80% of its volume. When aggregates are affected by neutron radiation, the concrete is severely affected as well. Similarly, aggregates are created by minerals, and the composition of minerals governs the overall response of aggregates to neutron irradiation because some minerals react to irradiation more than others. The crystalline lattice of minerals accumulates defects created by collisions of neutrons. These defects result in expansion that is then observed on aggregate samples. Besides the mineral expansion itself, also the difference in the expansion of minerals causes cracking within aggregates. The cracking can be observed on concrete samples in the transition zone between the cement paste and aggregates.

RIVE on aggregates can be generally described with a sigmoid curve that represents an expansion of the sample depending on neutron fluence. Since the matter cannot expand infinitely, the maximum RIVE indicates the level of saturation point, Figure 4.

Based on the available data, the maximum RIVE is observed on the level of neutron fluence $10^{19}$ n/cm$^2$ reported earlier as the level of neutron dose causing a decrease of the mechanical properties of concrete. Such a dose can be achieved during 40 or more years of reactor operation, Field et al. (2015).

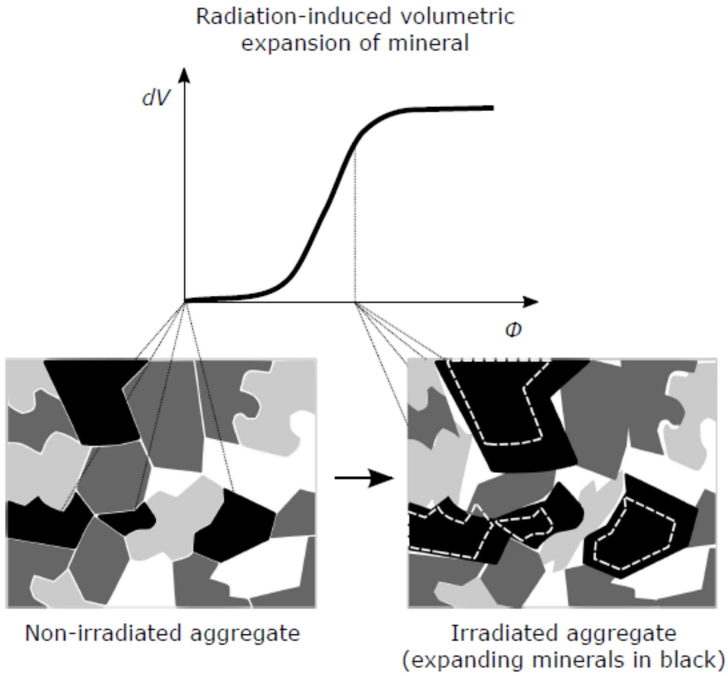


Figure 4. Mineral expansion in aggregates depending on neutron fluence.

## MESOSCALE MODEL

Simulations of mesoscale model of concrete samples in ATENA software is performed to validate applicability of FEM modelling of RIVE. In this model, the sample consists of a cement paste cylinder and embedded balls representing aggregate pieces, Figure 5.

The experiment chosen for the simulation has been performed by Kelly (1969) because samples have been irradiated by neutron radiation while the temperature has been kept very low at 40°C. The temperature of samples while irradiated very often exceeds 100°C; therefore, this experiment when temperature is kept low is chosen as no thermal damage needs to be assumed in this scenario.

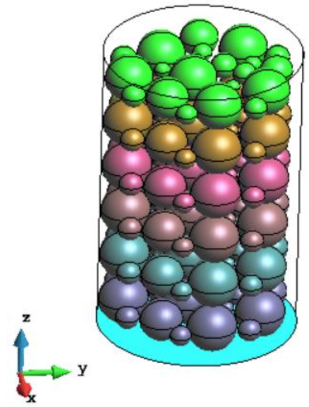


Figure 5. Mesoscale sample of cement paste cylinder with embedded aggregates.

The nonlinear material model for concrete in ATENA combines two constitutive models for compressive and tensile behaviour, Červenka and Papanikolaou (2008). The classical orthotropic smeared crack model with crack band is employed in tension (fracture), the Rankine criterion is assumed for the failure (when the maximal principal stresses are reached, the failure occurs) with exponential softening. The constitutive model in compression is based on Menétrey-William (1995) failure surface with hardening/softening parameter and non-associated flow rule based on nonlinear plastic potential function.

As has been mentioned above, the mesoscale model consists of two components, cement paste and aggregates. The cement paste is represented by nonlinear material where cracking and crushing can occur, while the aggregates are represented by elastic material that mainly inflicts the load into the sample. Material parameters are presented in Table 1.

Table 1: Material parameters for cement paste and aggregate.

| **Cement paste cylindric mean 70 MPa** | **Mean values acc. Model Code 2010** |
|---|---|
| Modulus of elasticity $E$ [GPa] | 41 |
| Poisson's ratio $v$ [-] | 0.2 |
| Compressive strength $f_c$ [MPa] | -70 |
| Tensile strength $f_t$ [MPa] | 5.7 |
| **Limestone aggregate - elastic** | **Values from Kelly (1969)** |
| Modulus of elasticity $E$ [GPa] | 72 |
| Poisson's ratio $v$ [-] | 0.2 |

Regarding the boundary condition of the model, the model is supported solely for the sake of the numerical solution and free expansion of the sample is allowed without constraint. The load is applied in the form of initial strain in aggregate pieces only. The cylinder diameter is 40 mm and the height is 60 mm which corresponds with the commonly irradiated concrete samples due to test reactor capsule sonstraints. The samples have been irradiated with three different levels of neutron fluence corresponding to three different dimensional changes that has been measured on aggregate samples, see Table 2.

The results of experiments and simulation are compared on measured expansion and decrease of tensile strength, see Figures 6 and 7. The expansion of samples correlates very well with experimental results, while tensile strength decrease is overestimated in simulations compared to experiments. However, the results of the Brazilian test (indirect tensile splitting test) tend to overestimate the actual tensile strength of the specimen; therefore, the tensile strength from simulations should be lower than experimental results. The standards recommend α value between 0.67 to 0.95 when transforming tensile strength from the splitting test ($f_{ctm,split}$) to mean tensile strength of concrete ($f_{ctm}$), see Equation 1, Model Code 2010 (2012).

$$f_{ctm} = \alpha f_{ctm,split} \quad (1)$$

Regarding the results from simulations and experimental ones, the elastic aggregate approach shows the good correlation with experimental data in both studied characteristics.

Table 2: Three levels of radiation dose with corresponding dimensional change of aggregate.

| **Radiation dose – fast neutrons [x10$^{19}$ n/cm$^2$]** | **Dimensional change in aggregate [%], Kelly (1969)** |
|---|---|
| 2.0 | 0.3 |
| 2.5 | 1.0 |
| 4.5 | 2.0 |

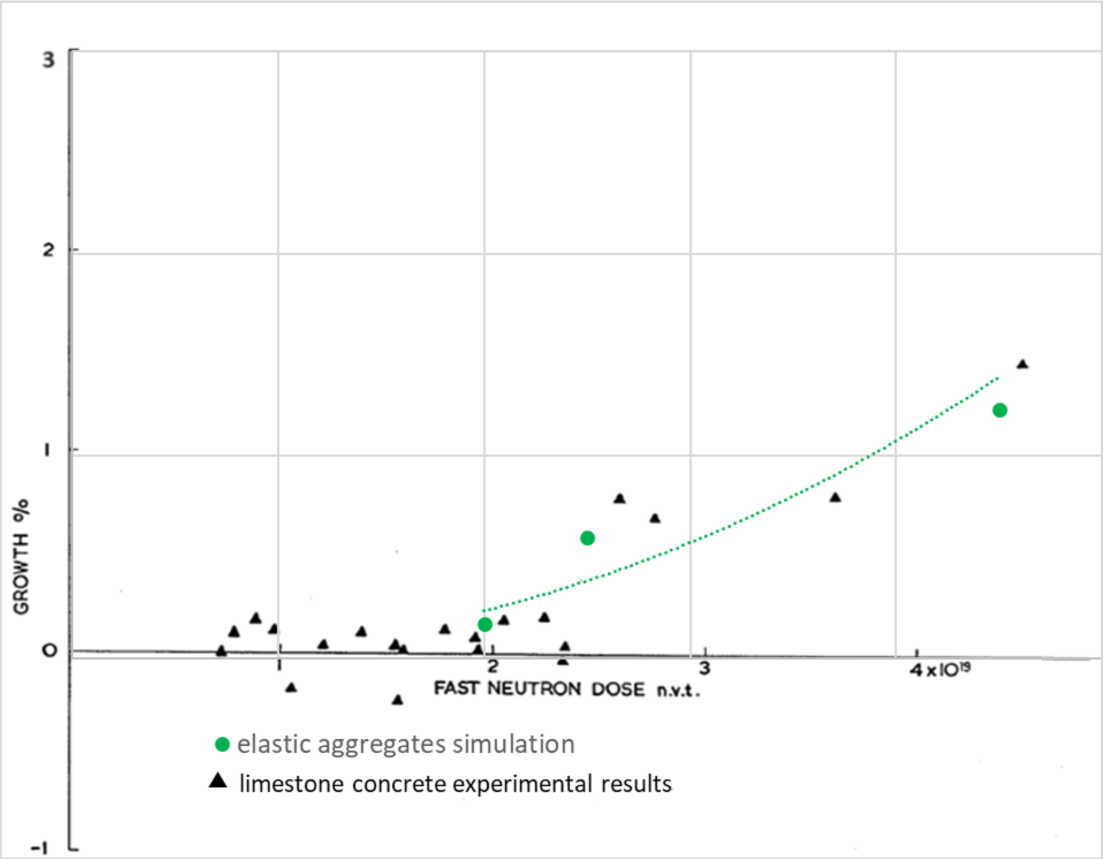


Figure 6. Results of experiment compared to simulation – expansion.

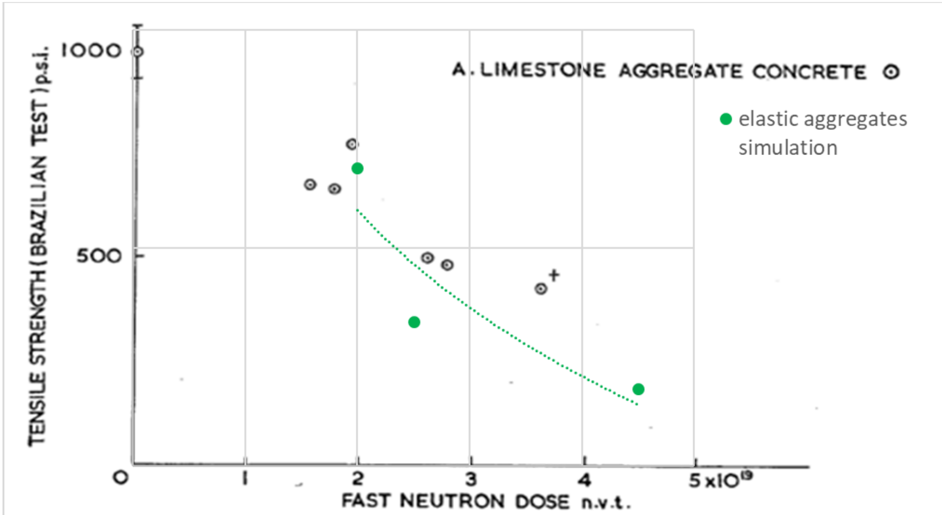


Figure 7. Results of experiment compared to simulation – tensile strength.

## MODEL OF BIOLOGICAL SHIELD

The last part of this work is dedicated to the study of actual concrete structure exposed to irradiation. The biological shielding is a protective structure around a nuclear reactor in a nuclear power plant. It can be assumed as one of the structures exposed to the highest radiation, especially around the active zone of the reactor. Its function is to protect every life form from radiation effects outside the shielding and in some cases, also to support the pressure vessel. Therefore, the soundness of the structure is essential for the safe operation of a nuclear power plant. VVER 1000 biological shield is showed in Figure 8 as an example.

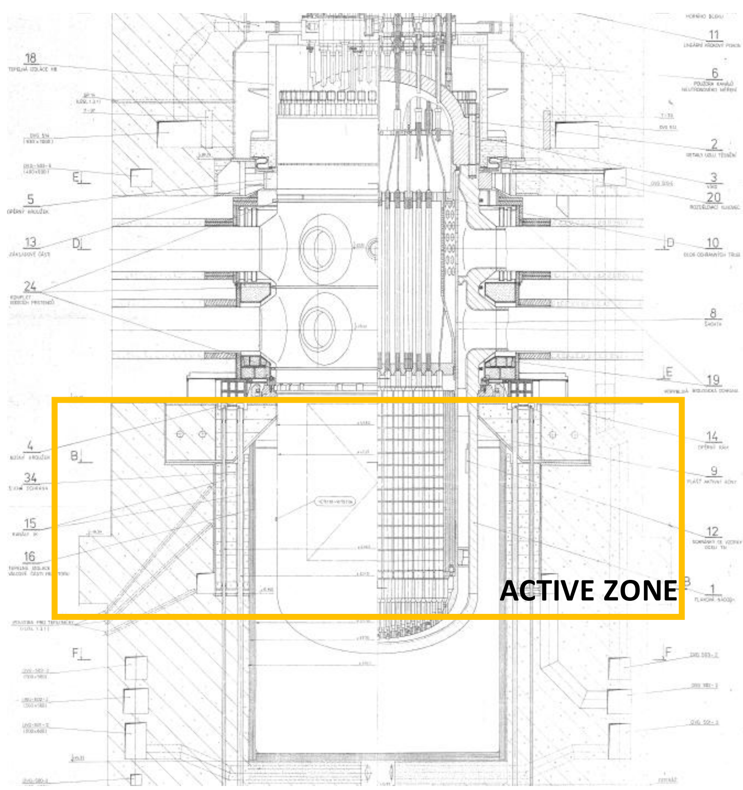


Figure 8. Drawing of vessel VVER 1000 with surrounding concrete biological shielding.

FEM model of irradiated biological shielding represented by symmetrical quarter is shown in Figure 9. The investigated part of the structure is the concrete ring around the active zone that is exposed to the highest flux of neutrons. The height of the active zone of the reactor is about 4.3 m, with the inner radius of the ring 2.885 m, and the thickness of the concrete shielding ring (including the load-bearing concrete) of 2.9 m resulting in the outer radius 5.785 m. The ring is supported on the side faces in X and Y directions to create symmetry conditions and also supported at the bottom in Z direction.

Then, the structure is loaded by three different loads. The first load is the self-weight of the structure, assuming 2300 kg/m$^3$; the second load is the weight of the reactor pressure vessel, which is about 800 t and is applied as pressure on the top surface of the ring. The third and last load is volumetric strain simulating the irradiation of the inner part of the ring structure. The depth of the structure that is affected by RIVE can be estimated from the calculation of the neutron radiation flux prepared by Remec et al. (2016), for the three-loop pressurized water reactor (PWR), while the VVER 1000 is four-loop PWR where the proposed estimate should be sufficient.

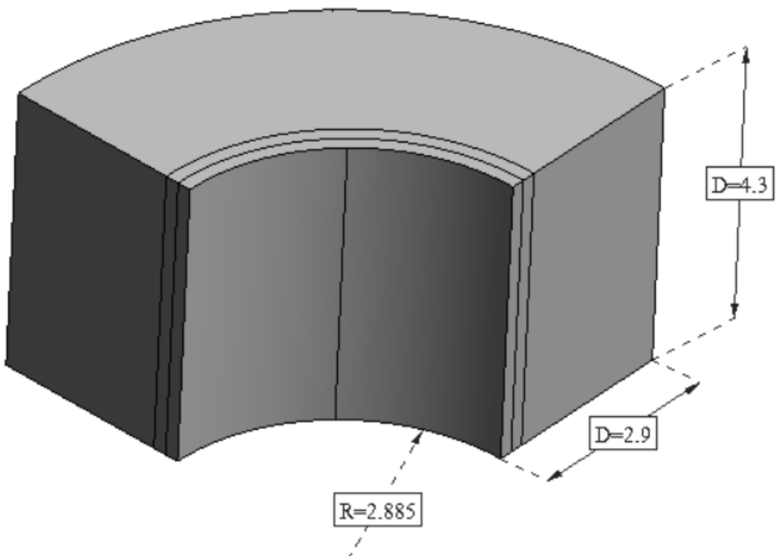


Figure 9. Symmetrical quarter of biological shielding around active zone for FEM simulation.

The flux of intermediate and fast neutrons (E>0.1 MeV) is assumed and should result in neutron fluence of order 1E+19 n·cm-2 within the 40 cm depth of the shield in 50 to 100 years of operation of the reactor. The maximal initial strain is 5% in all directions, resulting in a volumetric change of 16% that is the expected maximum of volumetric swelling of concrete reported in the literature, Field et al. (2015).

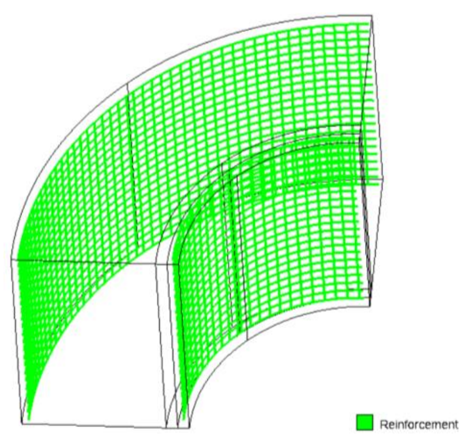


Figure 10. Reinforcement mesh on both surfaces of concrete ring.

Finally, the ring is theoretically reinforced with discrete bars creating mesh on the inner and outer surface of the ring. Spacing is 200 mm, and bar diameter is 16 mm see Figure 10. Reinforcement is represented by elastic-plastic material with a bilinear stress-strain diagram. All material parameters for concrete and reinforcement are summarized in Tables 3 and 4.

Table 3: Material parameters of concrete.

| **Material parameter** | **Value of parameter** |
|---|---|
| Modulus of elasticity $E$ [GPa] | 39 |
| Poisson's ratio $v$ [-] | 0.2 |
| Compressive strength $f_c$ [MPa] | -68 |
| Tensile strength $f_t$ [MPa] | 4.4 |
| Fracture energy $G_f$ [N/m] | 110 |
| Plastic strain $\varepsilon_{cp}$ [-] | -0.00084 |
| Critical com. displacement $w_d$ [-] | -0.0005 |
| Fixed crack [-] | 1 |
| Maximum aggregate size [mm] | 20 |
| Eccentricity [-] | 0.52 |

Table 4: Material parameters of reinforcement.

| **Material parameter** | **Value of parameter** |
|---|---|
| Modulus of elasticity $E$ [GPa] | 200 |
| Yield strength $f_y$ [MPa] | 550 |
| Ultimate tensile strength $f_s$ [MPa] | 577.5 |
| Ultimate strain $\varepsilon_s$ [-] | 0.025 |

The result of the simulation shows radial cracks through the shielding structure. This type of failure is most serious for the considered type of the structure because its shielding function is compromised. The radial crack width during simulation exceeds 10 mm. The visible cracks are shown in Figures 11 and 12. Excessive stress levels above yielding value are reached in the reinforcement mesh on the inner surface of the shielding where the RIVE load is concentrated, see Figure 13. Higher stresses are also reached on the outer surface where the cracks are developed.

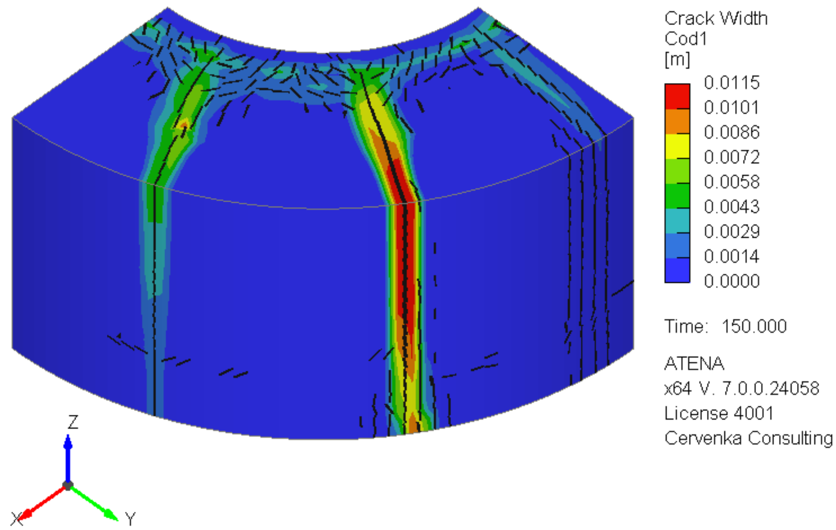


Figure 11. Concrete structure with crack width, including the filter of visible cracks (0.1 mm).

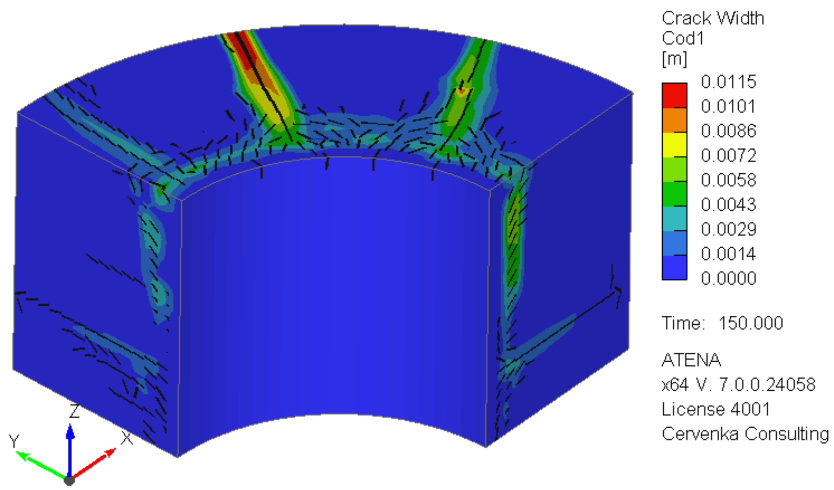


Figure 12. Concrete structure with crack width, including the filter of visible cracks (0.1 mm).

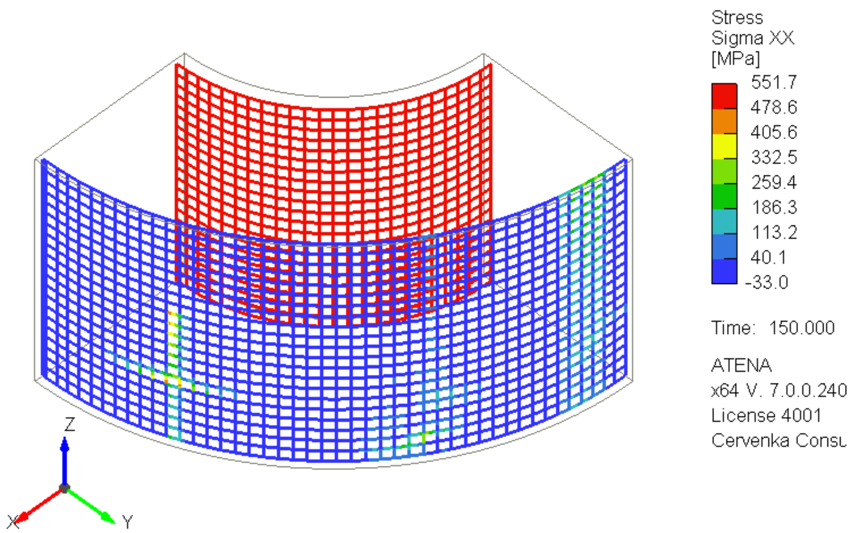


Figure 13. Reinforcement mesh with stress values.

## CONCLUSION

Radiation-induced effects on aggregates and concrete are presented, explaining the detrimental effect on concrete material. Radiation-induced volumetric expansion (RIVE) of aggregates leads to a reduction of mechanical properties of concrete, which should be investigated on the actual concrete structures in facilities subjected to the relicensing process. Some of these structures received the neutron dose that is expected to cause changes in material due to radiation exposure. For further investigation of the impact of irradiation on the structure, the simulation tools are involved.

The mesoscale model of irradiated aggregate embedded in the cement paste matrix is simulated, employing the FEM analysis using ATENA software. The aggregate RIVE represents load leading to crack development within the cement paste causing tensile strength reduction. The mesoscale model is validated on experimental data on irradiated concrete performed by Kelly (1969), who studied irradiation effects on concrete and its components. The results of mesoscale model correlate well with the experiment which proves efficiency of FEM modelling of concrete in such specific conditions.

Finally, the macroscale model shows significant risk of damage caused by RIVE in the structure of biological shielding. The demonstrative simulation reveals the potential of the development of radial cracks in the shielding structure, which are detrimental to the safety of the structure.

## ACKNOWLEDGEMENT

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