NUMERICAL MODELLING OF CONCRETE STRUCTURES EXPOSED TO RADIATION

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ABSTRAKT

Příspěvek se zaměřuje na numerické modelování betonových konstrukcí vystavených radioaktivnímu záření. Jsou popsány dva přístupy modelování konstrukcí - metoda konečných prvků a rigid-body spring modely.

Studie popisuje vylepšení konečně-prvkové analýzy betonového prstence biologického stínění, zejména posun od axisymmetrie k analýze 3D modelu, dále jsou zahrnuty časově závislé jevy jako je pokles vlastností betonu vlivem záření a dotvarování betonu.

V poslední řadě jsou představeny rigid-body spring modely jakožto potenciálně ideální přístup k simulování mechanické odezvy kvazikřehkých materiálů. Zmíněny jsou i složitost samotné diskretizace do Voroného diagramu, spojení elementů pomocí pružin a výpočet takového systému.

Zároveň jsou navržena vylepšení modelů pro budoucí práci.

KLÍČOVÁ SLOVA

Numerické modelování • 3D MKP • Dotvarování • Beton vystavený radiaci • Rigid-body-spring model

ABSTRACT

This study focuses on the numerical modelling of concrete structures exposed to radiation. Two modelling approaches are presented - Finite Element Method and Rigid Body Spring Models. Improvements to an FEM analysis of a concrete biological shield are presented, mainly the transition from axisymmetry to 3D, and also a deterioration of concrete properties due to irradiation and concrete creep. The basics of rigid body spring modelling are introduced as a potentially ideal approach for quasi-brittle material mechanical response exploration. Challenges of discretisation in Voronoi cells, element connection by springs and calculation of the discretised system are mentioned, as well as suggestions for model refinement in future work.

KEYWORDS

Numerical modelling • 3D FEM • Creep • Irradiated concrete • Rigid-body-spring model

1. INTRODUCTION

Concrete structures exposed to radiation, such as biological shields in nuclear facilities, require rigorous analysis to ensure their structural integrity and safety. This study presents improvements to the FE analysis program introduced in the previous thesis (Kovář (2023)). The program has been upgraded to analyse a 3D FE model, extended with time-dependent factors such as deterioration of concrete properties due to radiation exposure or concrete creep. In addition to the FEM model, the rigid body spring model is introduced. The motivation for using this modelling approach is that it allows the crack progression and width to be determined directly, making the modelling method ideal for quasi-brittle materials such as concrete. Also, consideration for future work is suggested to refine both FEM model and rigid body spring model.

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2. 3D FINITE ELEMENT MODEL

2.1. Numerical model description

In the previous work (Kovář (2023)), the axisymmetric FE model for analysing evolution of damage of a concrete biological shield subjected to radiation exposure was introduces. This study focuses on developing the program used for analysis of the structure, mainly the improvements suggested in the mentioned thesis. First, the necessity of a 3D model is suggested. A program for 3D FEA was made. The structure was divided into tetrahedral finite elements (see in the Fig. 1).

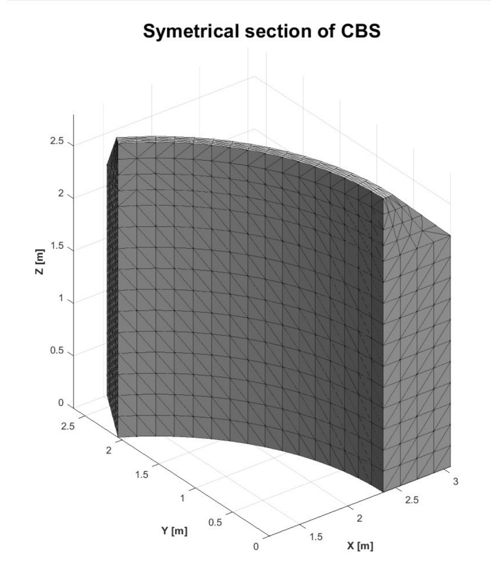

Figure 1: *3D model of CBS divided into tetrahedral finite elements*

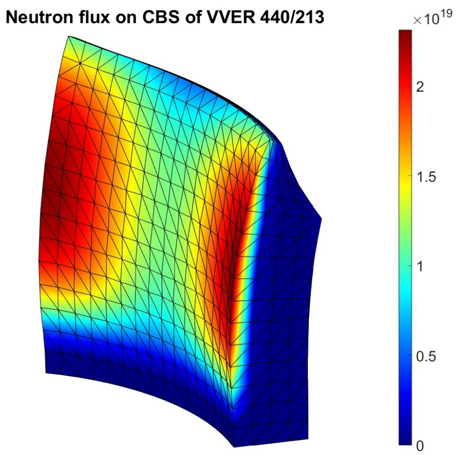

Figure 2: *Neutron fluence reduction according to the shape of active zone configuration*

Symmetry of the structures is exploited and only a *60 degree* section of the CBS is modelled. This fact allows shorter calculation time and allows taking the different neutron fluence in the horizontal direction into account as the fluence is repeating in 60 degree intervals as shown in the pictures (Fig. 2 or Fig. 3). The function of the horizontal fluence intensity is described by a coefficient ζ going from 0.5 to 1.0 in the interval by function depending on the horizontal angle φ (Eq. 1) of the given node (or integration point) where the load is applied.

$$\zeta(\varphi) = \frac{\cos(6\varphi)+3}{4}, \tag{1}$$

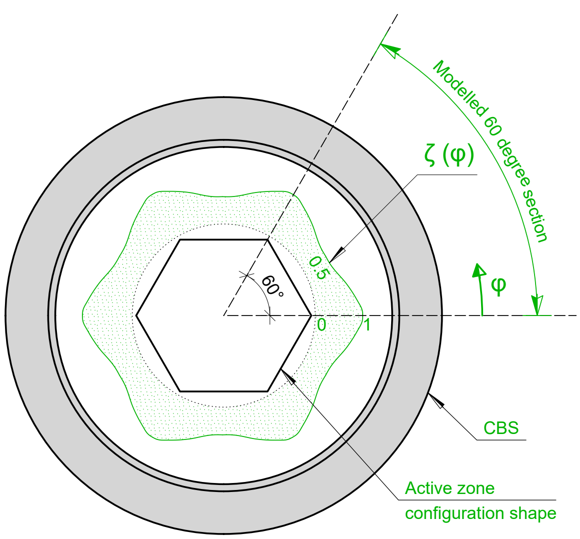

Figure 3: *Neutron flux on the deformed CBS structure*

Boundary conditions taking into account symmetry are applied on the vertical cut planes (plane XZ and the 60deg plane) through the master-slave method (or master-slave elimination). First, the master degrees of freedom are selected - in this case, the *x* displacements in nodes belonging to the XZ section plane (see Fig. 4) are chosen to be master and both *x, y* displacements on the other cut plane are slaves. By using the M-S elimination, equations belonging to these slave degrees of freedom are eliminated during the calculation and the stiffness matrix and load vector are modified accordingly (Felippa (2004)).

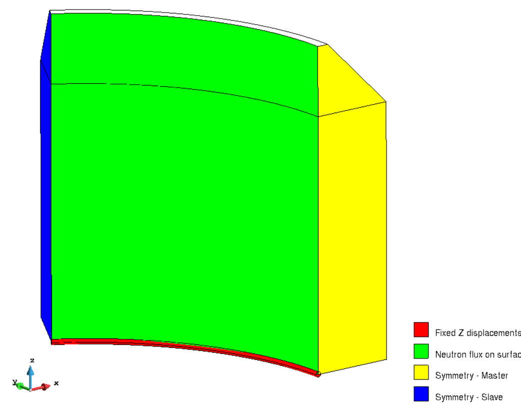

Figure 4: *Model with highlighted boundary conditions - fixed degrees of freedom and M-S elimination*

2.2. Time-dependent factors

Also, the time-dependent factors such as deterioration of concrete properties (Young's modulus and tension/compression strengths), see Fig. 5 that shows degradation of the parameters depending on the neutron fluence due to neutron irradiation is included in the analysis.

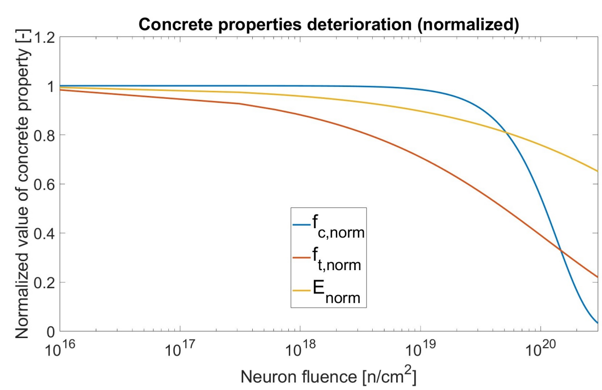

Figure 5: *Degradation of concrete properties as a function of neutron fluence*

Another time-dependent phenomenon that proved to have a significant, favorable impact is the creep of concrete (Kovář (2023), Le Pape (2015), Giorla et al. (2017)). In the case of CBS, the structure is not loaded constantly from the beginning but rather gradually throughout the years as the neutron flux accumulates, therefore, the stress-dependent strain is calculated applying hereditary approach:

$$\varepsilon_{cr}(t) = \sum_i J(t-\tau_i)\Delta\sigma_i$$

J denotes a compliance function. In the presented analysis, the function is constructed via the *fib* Model code 2010 approach (Taerwe et al. (2013)), $\Delta\sigma_i$ represents stress change in the integration interval and $\varepsilon_{cr}(t)$ is creep strain. The integration times are set in one year intervals. This approach assumes superposition principle. Following figure (Fig. 6, Kabele (2020)) illustrates the considered concept.

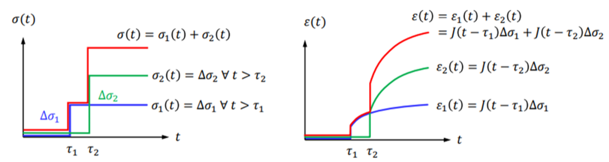

Figure 6: *Schematic representation of hereditary approach of creep strain determination*

3. RBSM

In addition to the finite element method, this study introduces the rigid-body spring models (RBSM), specifically a 2D model.

In contrast to the FEM, where the finite elements are perfectly connected and the elements are deformed, in the case of RBSM the structure is discretised in Voronoi cells with their seeds, representing the rigid bodies connected by a set of springs - 1 compression spring, 1 shear string and 1 rotational spring - with the respective stiffness k_N, k_τ and k_φ (see Fig. 7, Sofianos & Koumousis (n.d.)).

$$k_N = \frac{E' A_{face}}{p}, \qquad k_\tau = \frac{G A_{face}}{p}, \qquad k_\varphi = \frac{k_N d_{34}^2}{12},$$

where E' is effective modulus of elasticity ($E' = E(1-\nu^2)$), A_{face} is the area that is shared by neighbor cells, G is shear modulus, p is the distance of the two seeds and d_{34} is the distance of the two points of the neighbor cells.

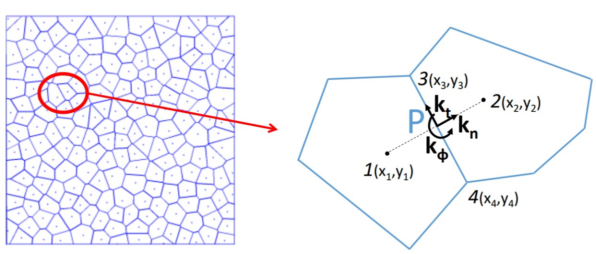

Figure 7: *Illustration of the discretization and connection of the rigid bodies*

The motivation for this approach is precisely this concept. The discretisation of irregular Voronoi cells together with the deformation of the springs can be used to model cracks directly and is therefore well suited for brittle and quasi-brittle materials, in contrast to FEM, where the determination of the exact crack width can be a challenging task involving advanced principles (e.g. crack band width) (Jirásek & Bauer (2012)).

3.1. Discretisation

The discretisation itself is not an easy task. The following section describes an algorithm for generating pseudo-random points based on Poisson-disk sampling. PDS is a commonly used method for generating cells for Voronoi discretisation. The basis of PDS is to find a set of n points at a given distance from a previous point. In this way an irregular grid of points with approximately equal distances is generated (Bridson (2007)). See the process of finding points from active points in Fig. 8 and the result in Fig. 10, Fig. 11.

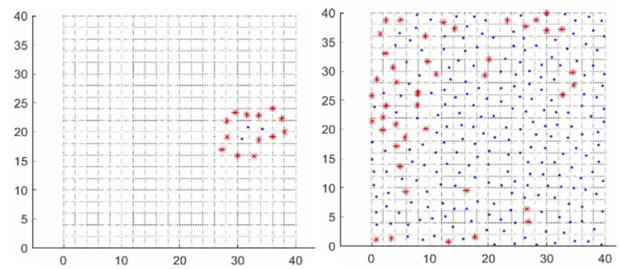

Figure 8: *Illustration of the PDS algorithm*

3.2. Calculation - testing

The developed software was tested on the smallest configurations in order to be able to visually assess the results clearly (only one or four elements loaded by a local force - see Fig. 9). Slightly more complex configurations have also been tested, these setups represent a real structure (a cantilever and a simple beam - see Fig. 10 and Fig. 11) but it is still relatively easy to assess the accuracy of the results.

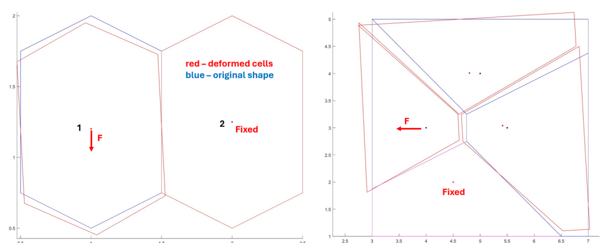

Figure 9: *Simple configuration of Voronoi cells to test the calculation*

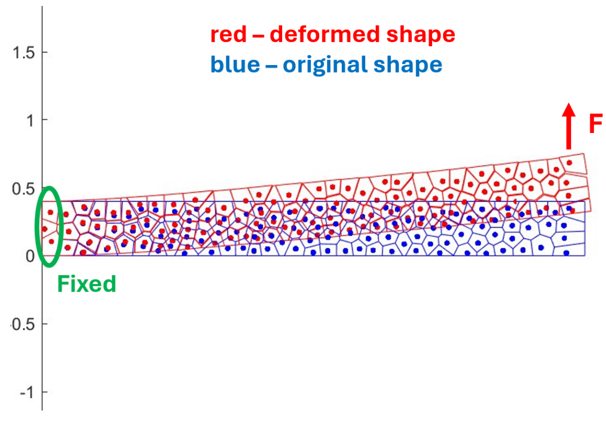

Figure 10: *Cantilever configuration of Voronoi cells to test the calculation*

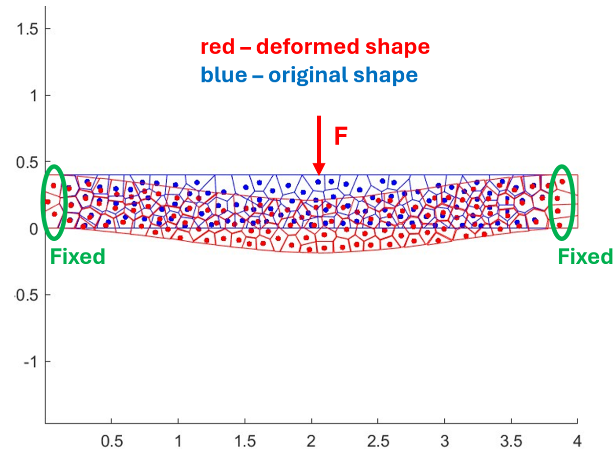

Figure 11: *Beam configuration of Voronoi cells to test the calculation*

Future work will extend the program to include a material non-linearity using the modified Mohr-Coulomb model of plasticity, which is a relatively simple model to be implemented in RBSM analysis (Bolander Jr & Saito (1998)) for concrete but allows the plastic deformation of springs to be modelled and the crack width (or more precisely the plastic deformations) to be simulated approximately.

4. SUMMARY AND CONCLUSIONS

In summary, this study presents two numerical modelling approaches for the analysis of concrete structures exposed to radiation in nuclear facilities. Firstly, the Finite Element Method analysis, which describes improvements to the aforementioned program, including upgrading to the analysis of a 3D FE model, consideration of variable neutron exposure in the horizontal direction, and incorporation of time-dependent factors into the analysis, such as progressive deterioration of concrete properties and creep, which appears to be a favourable factor in a damage-oriented analysis.

In addition, rigid-body spring models have been introduced. These models provide a different but effective approach to the direct simulation of crack propagation in materials, providing valuable insights into the mechanical response of concrete and other quasi-brittle materials. Future work is also proposed and will focus on refining these models and incorporating additional factors that influence the accuracy of numerical models of the response of concrete structures to radiation exposure.

ACKNOWLEDGEMENTS

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