Research

Mechanical Integrity of Canisters Using a Fracture Mechanics Approach

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SKI perspective

Background

In the current plans for the disposal of spent nuclear fuel in Sweden a copper canister is intended to be used. The mechanical integrity is given by an iron insert, while the outer copper shell gives corrosion protection.

The canister must be shown to withstand high pressure (during glaciations) as well as shear displacements in the rock. Earlier SKB and SKI work on canister integrity has been using FEM analysis of elastoplastic deformation. To get a better understanding of the influence of fracture initiation and growth in the insert, a fracture mechanics approach will be used.

The Boundary Element Method (BEM) is an numerical approach efficient for modelling fracture initiation and fracture growth. It can also be used for modelling contact and thermo-elastic stresses. For modelling of coupled temperature-stress-flow in the bentonite and fractured rock surrounding the canister, a FEM approach is more suitable. Thus a combined BEM/FEM approach will be used to study the coupled system of canister/bentonite/rock.

Purpose of the project

The purpose with the current project is to:
- develop numerical modelling capabilities for SKI to study the potential threats to mechanical integrity of the canisters using fracture mechanics approach as a complement to continuous deformation methods used before
- prepare SKI in needs for knowledge and understanding of key technical issues reviewing SKB’s studies on mechanical integrity of canisters.

The objectives of the project are:
- to investigate the possibility of initiation and growth of fractures in the cast-iron canisters under the mechanical loading conditions defined in the premises of canister design by Swedish Nuclear Fuel and Waste Management Co.
- to investigate the maximum bearing capacity of the cast-iron canisters under uniformly distributed and gradually increasing boundary pressure until plastic failure.

Results

The results of the BEM simulations, using the commercial code BEASY, indicate that under the currently defined loading conditions the possibility of initiation of new fractures or growth of existing fractures (defects) are very small, due to the reasons that the canisters are under mainly compressive stresses and the induced tensile stress regions are too small in both dimension and magnitude to create new fractures or to induce growth of existing fractures, besides the fact that the toughness of the fractures in the cast iron canisters are much higher that the stress intensity factors in the fracture tips.
The results of the FEM simulation show a approximately 75 MPa maximum pressure beyond which plastic collapse of the cast-iron canisters may occur, using an elasto-plastic material model. This figure is smaller compared with other figures obtained by SKB due to the reason that the FEM code (ADINA) has a different convergence iteration tolerance which prevents further increase of the load, and is therefore subjective to the numerical techniques applied for the plastic deformation analysis. A different maximum pressure may be possible if different convergence tolerance is adopted.

**Effects on SKI work**

This work will be used in the SKI evaluation of the SKB work on canister integrity. The report will also be used as one basis in SKI’s forthcoming reviews of SKB’s safety assessments of long-term safety and RD&D programmes.

**Project information**

Responsible for the project at SKI has been Christina Lilja.
SKI reference: SKI 2004/198/200509003
This report concerns a study which has been conducted for the Swedish Nuclear Power Inspectorate (SKI). The conclusions and viewpoints presented in the report are those of the author/authors and do not necessarily coincide with those of the SKI.
Summary

This report presents the methods and results of a research project for Swedish Nuclear Power Inspectorate (SKI) about numerical modeling of mechanical integrity of cast-iron canisters for the final disposal of spent nuclear fuel in Sweden, using combined boundary element (BEM) and finite element (FEM) methods.

The objectives of the project are: 1) to investigate the possibility of initiation and growth of fractures in the cast-iron canisters under the mechanical loading conditions defined in the premises of canister design by Swedish Nuclear Fuel and Waste Management Co. (SKB); 2) to investigate the maximum bearing capacity of the cast-iron canisters under uniformly distributed and gradually increasing boundary pressure until plastic failure. Achievement of the two objectives may provide some quantitative evidence for the mechanical integrity and overall safety of the cast-iron canisters that are needed for the final safety assessment of the geological repository of the radioactive waste repository in Sweden.

The geometrical dimension, distribution and magnitudes of loads and material properties of the canisters and possible fractures were provided by the latest investigations of SKB.

The results of the BEM simulations, using the commercial code BEASY, indicate that under the currently defined loading conditions the possibility of initiation of new fractures or growth of existing fractures (defects) are very small, due to the reasons that: 1) the canisters are under mainly compressive stresses; 2) the induced tensile stress regions are too small in both dimension and magnitude to create new fractures or to induce growth of existing fractures, besides the fact that the toughness of the fractures in the cast iron canisters are much higher that the stress intensity factors in the fracture tips.

The results of the FEM simulation show a approximately 75 MPa maximum pressure beyond which plastic collapse of the cast-iron canisters may occur, using an elasto-plastic material model. This figure is smaller compared with other figures obtained by SKB due to the reason that the FEM code (ADINA) has a different convergence iteration tolerance which prevents further increase of the load, and is therefore subjective to the numerical techniques applied for the plastic deformation analysis. A different maximum pressure may be possible if different convergence tolerance is adopted.
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1. INTRODUCTION

For the mechanical integrity of canisters for nuclear waste disposal, the numerical modelling works so far have focused on continuous deformation of the canisters as either a whole or its parts (such as lid and cylinder). Initiation and potential growth of fractures has not been investigated by using either numerical modelling or experiments. The issue of fracturing may become significant especially when the defects are located at some critical places of the cast iron insert. It has been noted in the past that mechanical safety of canisters depends on not only its deformation or stress, but the potential of fracture initiation and growth under possible extreme loading conditions, since formation of fractures or growth of defects will lead to the loss of functionality of the canister no matter its deformation is small or large. A canister keeping its mechanical integrity without holes or fractures may still serve as an isolation barrier to a certain extent, even if its deformation is large. Research on potential fracturing process of the canister as a whole or any integral parts of it is also needed. The most obvious way ahead is then the fracture mechanics approach instead of continuous deformation approach.

An efficient numerical approach dealing with fracture initiation and growth issues is the Boundary Element Method (BEM) since its efficiency for direct accommodation of fracture initiation and growth without artificial re-meshing difficulties as encountered when a FEM approach is used. The non-linear behaviour of the canister and fractured rocks, such as plastic deformation and fracturing, is most efficiently modelled using FEM based on continuum approach.

The above concepts are the basis for the current project for numerical modelling of mechanical integrity of canisters. The aims of the project are:

i) Testing the proposed test cases in the SKB’s canister design premises with the alternative bentonite swelling pressure distributions to examine the risks of the fracturing processes, by placing one or a few number of hypothetic defects in sensitive locations in the canister and observe its possible development and potential effect on the mechanical integrity of the canister, using a linear elastic fracture mechanics approach with the BEM code (BEASY). The problem was considered as three-dimensional, but with symmetry conditions considered whenever the geometry and boundary conditions permit.

ii) Testing the collapse load of the cast iron insert, using an elasto-plastic approach with a FEM code ADINA. The problem was considered as two-dimensional with a 1/8 symmetry for both geometry and loading condition.

The canister design geometry and loading cases as defined in Werme (1998). Only the BWR types of cast iron insert was considered since it represents the more risky cases.
2. THE LOADING CASES

The main loading conditions considered are the two cases in the canister design premises defined in Werme (1998), with differential mobilization of swelling pressure (see Fig. 1), one case with possible deviations of fuel hole positions (thus causing unsymmetric geometry and change of thickness of the separation of the cast iron insert, another case of a generic simulation for defining the utmost collapsing loads required to produce plastic deformation using FEM. In theory, the loading cases should apply to both PWR and BWR types of canisters, but only the BWR type was considered since this geometry is the more risky type with more fuel holes.

![Figure 1. Two extreme loading cases of uneven distribution of swelling pressure considered for canister design (Werme, 1998).](image)

A different loading case considered in SKB design and analysis of canister safety is a 200 mm shear displacement along a fracture in rock, intersecting the canister. For this case, the locations of the rock fracture and its orientation, and the bentonite deformation with dry, partial or full saturation should be incorporated. Due to such complexity this loading case is not considered in this report.

For all the cases, the modeling starts with stress analysis without fractures. Results will indicate the critical locations with largest tensile stress concentrations. An initial fracture can then be inserted to the locations with tensile stresses under the same loading conditions to examine its potential for growth.

**Loading case (a) (Fig. 1a)**

The swelling pressure is fully developed (with 44 MPa) on one side of the canister's cylindrical surface and on the end surfaces. On the other side of the cylindrical surface, the swelling pressure is 20% of the mobilized along the central half and 20% reduced along the remaining quarters at the ends of the canister. Due to the non-symmetric loading conditions, a 3D model with a 1/4 canister is required.

**Loading case (b) (Fig. 1b)**

The swelling pressure is fully developed around the bottom half of the canister, while the swelling pressure is 20% lower around the top half. The resulting upward force, which results from the differences in pressure against the canister's end surface, is balanced by a shear force along the bottom half of the cylindrical surface.
c) Loading case (c) (Fig. 2)
This loading case was considered for possible effects of deviation of the fuel hole positions from the design. A shift of 1, 2, 5 and 10 mm of the fuel hole location in one direction is considered (Fig. 2) so that the original thickness of separation $d$ is changed. The load on the outer surface is 44 MPa of the maximum design load.

d) Loading case (d)
This case is defined for a generic study of the utmost collapsing loads the cast iron insert may bear without any initial defective fracture. A uniformly distributed external load will be increased incrementally until the insert loses its structural stability with plastic flow. Full symmetric condition should be used for the BWR type, without considering the inner tubes inside the fuel holes and the copper shell. The radius of the corner of the fuel holes should be considered with the latest design considerations.

The above loading cases are considered to represent minimum requirements considering only one case of fracture number, size and location, and one case of the radius of the corners of the fuel holes in the cast iron insert.

<table>
<thead>
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<th>BWR type</th>
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| **Boundary conditions**
$x = 0$ boundary: fixed in $x$-direction
$y = 0$ boundary: fixed in $y$-direction
$z = 0$ boundary: fixed in $z$-direction
Confining pressure: $P_c = 44$ MPa |
| **The location of fuel holes**
$\Delta y = 1, 2, 5$ and $10$ mm |

a) Boundary conditions for sensitivity analysis for BWR type

b) A slice of 230 mm in thickness for the 3D model geometry

Figure 2. Model geometry and loading condition for loading case (c) -BWR type.
3. MATERIAL PROPERTIES

The elastic properties of the cast iron are the Young’s modulus ($E$) and Poisson’s ratio ($\nu$), given by $E = 170$ GPa and $\nu = 0.3$. The fracture toughness parameters are listed in Table 1, which is obtained from measured data at the Solid Mechanics Division at KTH (Nilsson, 2005).

Table 1 Fracture toughness parameters for Mode I fracture.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$J_{IC}$ value</th>
<th>Parameters</th>
<th>$K_{IC}$ value</th>
</tr>
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<tr>
<td>$J_{IC}$ (+23 °C, mean) [kN/m]</td>
<td>47.1</td>
<td>$K_{IC}$ (+23 °C, mean) [MN/mm$^{3/2}$]</td>
<td>2.964</td>
</tr>
<tr>
<td>$J_{IC}$ (0 °C, mean) [kN/m]</td>
<td>28.5</td>
<td>$K_{IC}$ (0 °C, mean) [MN/mm$^{3/2}$]</td>
<td>2.306</td>
</tr>
<tr>
<td>Initial fracture length [mm]</td>
<td>1, 2, 5 and 10</td>
<td></td>
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The $K_{IC}$ values are calculated from $J_{IC}$ values using the following equation (Broek, 1986)

$$J_{IC} = \frac{1 - \nu^2}{E} K_{IC}$$

(1)

The plastic material properties are described in Chapter 5 for loading case d), where it is more appropriate.

To help readers unfamiliar with concepts of fracture mechanics in use of the above parameters for fracture growth modeling, a short description is given below.

In the linear elastic fracture mechanics, the fundamental postulate is that the fracture behaviour is determined by only the values of the stress intensity factors (SIF) which are a function of the applied load and the geometry of the fractured structure (Broek, 1986). The stress intensity factors thus play a fundamental role in linear elastic fracture mechanics applications.

Fracture growth processes are simulated through an incremental fracture extension process. For each increment of the fracture extension, a stress analysis is carried out and the stress intensity factors are evaluated. The crack path is computed by a criterion defined in terms of the stress intensity factors.

In general, numerical methods were used for the evaluation of the stress intensity factors around the crack tip. In the BEASY code, the stress intensity factors are computed using opening displacement method for the 3D problems. The calculated stress intensity factors around the crack tips are compared with the critical values of the fracture toughness. Fracture extension will take place if the calculated stress intensity factors, $K$ exceed a critical value, $K_C$. It should be noted that in most of fracturing processes, the role of shear modes (mode II and III) will be subordinate to that of the tensile mode (mode I). Hence, the calculated stress intensity factor for the mode I, $K_I$ is always compared with a critical value, $K_{IC}$.

In determination of fracture toughness in lab, instead of evaluating directly the $K$ values, the values of the so called $J$ integral is often used as a fracture criterion. The critical value $J_{IC}$ is measured during the toughness tests, and $J$ is interpreted as an energy release rate. The fracture will propagate if values of $J$ exceed $J_{IC}$. The $K_{IC}$ and $J_{IC}$ values are related through equation (1) and this relation is valid for the linear elastic fracture mechanics applications.
4. RESULTS OF FRACTURING POTENTIALS

The presentation of the numerical simulation is given in the order of loading cases c)-a)-b)-d) with increasing complexity in either model geometry, loading condition or material behaviour.

4.1 Results of loading case c)

Figure 3 shows the BEM mesh for the model with loading case c), for pure stress calculations without fractures. The boundary condition is a 44 MPa radial load on the outer surface as shown in Fig. 2a. A 1/4 geometric symmetry was assumed.

Figures 4-10 present the 3D distributions of the maximum principle stress ($\sigma_1$), Von Mises effective stress, and displacement as iso-value contour maps, for the cases of no-deviation of the fuel hole position, and with 1mm, 2mm, 5mm and 10mm shifting in the y-direction, respectively. It is shown that with no such deviations, the maximum tensile stress of small magnitude (< 65 MPa) occurs on the wall of the two fuel holes closest to the outer surface of the insert and the maximum Von Mises effective stress of also small magnitude (< 460 MPa) occurs at the two corners of the same two fuel holes, respectively. With such small magnitudes of tensile stress and Von Mises effective stress, it is not likely that any fracture could initiate at all, and no existing fractures with given toughness in Table 1 will grow either. However, for confidence in results and evaluation, four fractures were inserted on the wall and at the corners of the two fuel holes (Fig.11) where maximum tensile stresses are found, and simulation of the possible growth of these fractures were conducted. Figure 11 a and b indicate their general locations in the BEM mesh and Figure 11c shows the details of the fracture geometry and mesh before loading is started. The initial length of the fractures (defects) are assumed to be 1, 2, 5 and 10 mm, respectively to test the sensitivities of fracture growth with fracture size (Fig.12).

The results of the analysis, as the SIF (stress intensity factor) for three modes of fracturing at the mesh points (MP) along the tips of inserted initial fractures as manufacturing defects, are presented in Tables A1-A20 in the Appendix as calculated stress intensity factor (SIF) at the crack tip mesh points with initial crack size of 1, 2, 5 and 10mm, for the case without fuel hole deviation, and with deviations of 1, 2, 5 and 10mm, in the y-direction, respectively. Observation of these tables indicate that all SIF at these fracture tips are less than the $K_{IC}$ value in Table 1. The fractures in all cases therefore do not grow, due to mainly two reasons: 1) fracture toughness of the cast iron is adequately high; 2) the magnitude and distribution areas of the tensile stresses are very small. Therefore there is no enough mobilized energy by the tensile stress field to overcome the resistance of the fracture toughness in order to create additional fracture surfaces from the tip front to make the area of existent fracture increase (fracture grow).

Note that the numbers of mesh point in Tables A1-A20 are not the real node numbers in the BEASY models for this set of calculation. These node numbers changes with changing fracture size and location in each model, but the total number of mesh point along each fracture are the same (15 points). Therefore the same geometrical locations and numbering of these points as shown in Fig. 13 are used to indicate their locations.
and order, for all cases of loading case c) in order to avoid repetitive drawing of the same plots.

When initial fractures are inserted into the models, their tips may sometimes penetrate into compression stress areas if their initial size is larger than the thickness of the tensile stress zone (which is usually very thin as shown in Figs. 4 and 6). This penetration is one of the reasons that negative SIF values were obtained at many mesh points along fracture tips due to the dominance of nearby compressive stress fields, due to the special sign convention used in the BEASY code when the SIF is calculated.

In comparison between the simulated cases, the case of fracture of 1 mm in size with or without fuel hole position deviation generates maximum value of SIF, indicating this case is the closest condition toward possible fracturing, but still far from reaching a critical state for fracture growth.

In general, this set of simulation results show that no crack growth will be caused due to deviation of fuel hole deviations up to 10 mm, in either y- or z-direction (due to symmetric geometry of the canister), due to dominance of the compressive stress field, small magnitude of tensile stresses on the wall of fuel holes, and adequate fracture toughness of the cast iron. This conclusion may be extended to general deviations of fuel holes no more than 10 mm due to the same reasons as mentioned above, since such deviations will not likely generate very extensive distributions of tensile stresses of very large magnitude.

Figure 3. Calculation mesh of a slice of BWR type canister using BEASY code (for stress calculation).
Figure 4. Results of stress analysis for BWR type canister without movement of the fuel hole location, a) maximum principle stress ($\sigma_1$ plot) and b) von Mises effective stress.

Max = 39.081
Min = -50.322
Unit: MPa

Max = 435.17
Min = 41.587
Unit: MPa
Figure 5. Displacement of BWR type canister without movement of the fuel hole location in the a) $x$-, b) $y$- and b) $z$-directions.

Max = 7.13479E-3
Min = -0.31649
Unit: mm

Max = 7.07555E-3
Min = -0.31771
Unit: mm

Max = 7.04362E-3
Min = -1.84839E-4
Unit: mm
Figure 6. Results of stress analysis (maximum principle stress, $\sigma_1$ plot) for sensitivity analysis in terms of the fuel location, a) 1 mm, b) 2 mm, c) 5 mm and d) 10 mm dislocations.
Figure 7. Results of stress analysis (von Mises effective stress) for sensitivity analysis in terms of the fuel location, a) 1 mm, b) 2 mm, c) 5 mm and d) 10 mm movements.
Figure 8. Displacement of BWR type canister in the x-direction with deviation of the fuel hole location by a) 1 mm, b) 2 mm, c) 5 mm and d) 10 mm, respectively.
Figure 9. Displacement of BWR type canister in the $y$-direction with deciation of the fuel hole location by a) 1 mm, b) 2 mm, c) 5 mm and d) 10 mm.
Figure 10. Displacement of BWR type canister in the z-direction with deviation of the fuel hole location by a) 1 mm, b) 2 mm, c) 5 mm and d) 10 mm.
Figure 11. BEM mesh and the introduction of initial cracks at the maximum tensile stress area: a) Perspective view of the inserted fractures; b) Top view of the locations of the inserted initial fractures, and c) details of the fracture geometry with BEM mesh.
Figure 12. Top view of the initial crack with different length of 1, 2, 5, and 10 mm, respectively.

Figure 13. Locations of mesh point (MP) and their numbering convention along the tip of the inserted fracture.
4.2 Results of Loading case a)

Figure 14a illustrates the model geometry and boundary conditions for loading case a), according to Werme (1998). In order to make the model computationally possible with manageable sizes and memory requirements for 3D calculations, 1/4 symmetry was assumed so that slight changes from the original definition as in Werme (1998) is made, including the roller boundary conditions at one end of the canister. This slight change may not, however, change the stress distribution situation very much since the general distribution of the swelling pressures along the canister as described in Werme (1998) is followed.

Figures 15 and 16 show the results of loading cases a) without fracture, for maximum principal stresses (including tensile stress) and Von Mises effective stress distributions (Fig.15) and displacement (Fig.16). The maximum tensile stress can be observed at the fixed end of the canister and may, therefore, be due to boundary-end effects of numerical artefacts. More realistic tensile stresses are much smaller in magnitude (less than 25 MPa, Fig.15a) along the corner of the fuel hole. Similar situation can also be observed for distribution of the Von Mises effective stress (Fig.15b). This indicates that critical locations for fracture introduction should be along the two corners of the two fuel holes, as shown in Fig.17. The fracture size is assumed to be 1 mm, according to comparison results from loading case c).

The resultant SIF as calculated for the two initial cracks are listed in Table A21 of the Appendix. The mesh point numbers, in this case, are the actual node numbers in the model, with their locations along the fracture tipes shown in Fig. A1 of the Appendix. The calculated SIF is far smaller compared to the measured $K_{IC}$ value so that cracks did not grow at all. The reasons for this results are the same as that for loading case c) as mentioned before.

4.3 Results of loading case b)

The loading case b) is simulated in parallel with loading case a) due to the similarity of the conceptualization of the model geometry and boundary conditions (Fig.14b), with, however, more justified symmetric conditions.

Loading case b) generated similar tensile stress and Von Mises effective stress distributions and magnitudes, as shown in Fig. 18, although with slight increase of tensile stresses at the fixed end of the canister, due to numerical boundary-end effects. Figure 19 shows the distribution of the displacements in $y$- and $z$- directions, with small magnitudes. The more realistic tensile stress area are also the two corners of the fuel holes as in loading case a), where two fractures of 1mm in size were inserted as shown in Fig. 20. The resultant SIF as calculated for the two initial cracks are listed in Table A22 of the Appendix. The mesh point locations and numbering numbers are shown in Fig.A2 of the Appendix. Similar results were calculated for SIF, with no fracture growth observed due to the same reasons as given before.
4.4 Summary on fracture growth potentials

The simulations presented above for different loading conditions as considered in Werme (1998) and with consideration of possible fuel position deviations show that there is no risk of growth of initial fractures (due to manufacturing processes), due to the dominance of compressive stress field, high value of toughness of cast iron and low tensile stress magnitude in combination.

Figure 14. Two extreme loading conditions of uneven distribution of swelling pressure for full scale model based on Werme (1998) for fracture simulations. A quarter cross section of BWR type canister was used for stress calculation and fracture simulation by BEASY code. It should be noted that the stress values for 20, 80, 100 and 120 % are 8.8, 35.2, 44 and 52.8 MPa.
Figure 15. Results of stress analysis for full scale BWR type canister with loading case a), a) Distribution of maximum principle stress ($\sigma_1$ plot) and b) Distribution of von Mises effective stress.
Figure 16. Displacement of full scale BWR type canister with loading case a) in the 
a) $x$-, b) $y$- and c) $z$-direction.

Max = $1.1879 \times 10^{-2}$
Min = $-0.35948$
Unit: mm

Max = $1.43549 \times 10^{-2}$
Min = $-0.26404$
Unit: mm

Max = $8.21186 \times 10^{-3}$
Min = $-5.76517 \times 10^{-2}$
Unit: mm
Figure 17. Introduction of two initial cracks at the maximum tensile stress area for loading case a).
Figure 18. Results of stress analysis for full scale BWR type canister with loading case b, a) Distribution of the maximum principle stress ($\sigma_1$ plot) and b) Distribution of the von Mises effective stress.
Figure 19. Displacement of full scale BWR type canister with loading case b in the a) x-, b) y- and c) z-direction.

Max = 1.63322E-2
Min = -0.26664
Unit: mm

Max = 1.63698E-2
Min = -0.26659
Unit: mm

Max = 5.26918E-4
Min = -0.81935
Unit: mm
Figure 20. Introduction of initial crack at the maximum tensile stress area for loading case b.
5. RESULTS OF PLASTIC COLLAPSE OF THE CAST IRON INSERT

The plastic collapse load of the cast iron insert was simulated using a 2D FEM code ADINA. The basic concept is to gradually increase the uniformly distributed radial normal load on the outer surfaces of the insert until no more increment of load can be added without causing divergence of the solution, or buckling failure of the whole insert. Similar simulations were conducted by SKB as reported in (Dillström, 2005; Andersson et al., 2005). The objective of this FEM simulation is to re-evaluate the important issues related to this problem. In order to have a common basis of comparison with SKB works reported in (Dillström, 2005; Andersson et al., 2005), the insert geometry dimension and material constitutive model and properties used in these reports were adopted.

The ADINA code is a widely applied FEM code for structural analysis with linear elastic and non-linear elasto-plastic material models. The features of the code is well known and do not need to be repeated here. The specific code applied to this simulation, however, is a research-oriented code developed from an earlier version of the ADINA code group (Zhang, 2006), with general functionality and a library suite of constitutive models for structural analysis with elastic and elasto-plastic behaviours.

5.1. Geometry mode

Due to the symmetry in both insert geometry and boundary conditions, only 1/8 of the insert needed to be included in the finite element model. The resulting finite element model is shown in Figure 21, using outer radius = 474.5 mm and the corner radius = 20 mm, respectively.

Figure 21. Finite element model used for loading case d) for plastic collapse analysis.
5.2. Material Properties

The calculations were made using a simplified multilinear elastic-plastic material model for the cast iron. The stress-strain curve of the material is defined as piecewise linear in the strain-stress space, based on a Von Mises yield surface and an associated flow rule, with isotropic multilinear hardening. The material properties used include: Young's modulus $E = 160000 \text{N/mm}^2$, Poisson’s ratio $\nu = 0.286$, yield stress $R_{0.2} = 270 \text{N/mm}^2$, strain at $R_{0.2}$ ($\varepsilon_{y} = R_{0.2} / E = 0.0016875$, respectively. The other parameters are: at strain $\varepsilon_{u1} = 0.1$ the ultimate strength $R_{u1} = 480 \text{N/mm}^2$; at strain $\varepsilon_{u2} = 0.3$ the ultimate strength $R_{u2} = 580 \text{N/mm}^2$, respectively.

5.3. Analysis results

5.3.1 Stresses and stress concentrations

Figures 22-29 present the distributions of the Von Mises effective stress with the normal load ($p$) at outer surfaces equal to 15, 25, 35, 45, 60, 65 and 75 MPa, respectively. These figures demonstrate the evolution of stress concentration areas during increasing pressure at the outer surface of the cast iron insert. These areas of stress concentration starts at the upper right corner of the fuel holes closest to the outer wall (Fig.22), then spread in the walls, especially the separation parts between the fuel holes (Figs. 23-28). The changes in the geometry when the outer pressure reaches 75 MPa are shown in Figs. 29 and 30 at enlarged scales. Tensile stresses of small magnitudes appears then at the outer surface and inner wall surfaces (the red crosses in the stress vector plot of Fig.31), as also predicted by the BEM models presented in Chapter 4. Figures 32-35 show the distributions of the maximum principal stress $\sigma_1$ with increase of the pressure on the outer surface.

![Figure 22. Von Mises effective stresses when $p = 15$ MPa.](image)
Figure 23. Von Mises effective stresses when $p = 25$ MPa.

Figure 24. Von Mises effective stresses when $p = 35$ MPa.
Figure 25. Von Mises effective stresses when $p = 45$ MPa.

Figure 26. Von Mises effective stresses when $p = 60$ MPa.
Figure 27. Von Mises effective stresses when $p = 65$ MPa.

Figure 28. Von Mises Effective stresses when $p = 75$ MPa.
Figure 29. Final collapse geometry (collapse analysis using ADINA), plot of the effective stress at the final collapse pressure = 75 MPa.

Figure 30. Effective stresses close to the corner radius when $p = 75$ MPa.
Figure 31. Principal stress vectors close to the upper right corner of the hole closest to the outer surface of the insert. The red crosses indicate tensile stresses.

Figure 32. Principal stress ($\sigma_i$) when $p = 45$ MPa.
Figure 33. Principal stress ($\sigma_1$) when $p = 50$ MPa.

Figure 34. Principal stress ($\sigma_1$) when $p = 60$ MPa.
In all cases the stress state of the insert was mainly compressive. When the external pressure is below ~ 30 MPa a stress concentration (in compression) dominates the stress field at the fuel channel closest to the outside surface of the insert.

As already stated above, the stress state of the insert was mainly compressive, but there was also a region with tensile stresses at the fuel channel facing the outside of the insert (see Figs. 32-35). The size of the region with tensile stresses increased with the applied pressure and also increased as the corner radius became smaller or as the fuel hole eccentricity became larger. The stress component that is most interesting, regarding initiation of crack growth, is related to the principal stress ($\sigma_1$) if in tension. The largest principal stress in tension is located within the material (when the external pressure is below ~ 45 MPa, Figs. 31 and 32) or at the inner surface (when the external pressure is above ~ 45 MPa, Figs. 33-35), which is of the similar magnitude and location as calculated by the 3D BEM BEASY models presented above. However, their magnitude is not large enough to create new fractures.

### 5.3.2 Plastic strain (flow)

The plastic strain (flow) is the main variable for evaluating the stability of the insert. As the external pressure increases, also the plastic strain (flow) increases until a local collapse of the ligament occurs, as shown in Figs. 36-39. The plastic strain concentrates around the upper right corner of the fuel hole closest to the outer surface of the insert and starts near the corner with a small area (Fig. 36). With increasing external pressure, the concentration area increases from the corner outwards to the outer surface, when the external pressure is no more than 55 MPa (Fig. 37). Beyond this pressure, not only the
plastic flow concentration near the corner grows further and reaches the outer surface, but also occurs in one of the ligaments (separating the fuel holes), Fig. 38. At the external pressure = 75 MPa, Fig. 39, a large plastic strain area connecting the corner and the outer surface of the insert is created, and all ligaments of the fuel holes are under plastic strain (flow) conditions. This indicates that a plastic collapse will occur. In the FEM simulations, at \( p = 75 \) MPa, convergence of plastic strain calculation cannot be maintained with the built-in plastic strain iteration algorithm, indicating the structure is close to final collapse.

Figure 36. Effective plastic strains when \( p = 45 \) MPa.

Figure 37. Effective plastic strains when \( p = 55 \) MPa.
Figure 38. Effective plastic strains when $p = 65$ MPa.

Figure 39. Effective plastic strains when $p = 75$ MPa.
It should be noted that the total collapse of the insert is determined not only by the formation of plastic flow region between the corner and outer surface, but also, or even more importantly, determined by the plastic states of the ligaments. Structural stability of the insert can be lost only when all ligaments enter the plastic flow state. This state is achieved at outer external pressure of 75 MPa as indicated in Fig. 39.

The external pressure of 75 MPa is therefore defined as the final plastic collapse load of the insert. However, this only indicate the start of total collapse, not necessarily the absolute final collapse load since serious buckling failure of the ligaments have not occurred. More load can still be added to produce total buckling failure of the ligaments, which cannot be performed by the current FEM code.

Figure 40 show the external pressure and displacement in the z-direction in one of the ligament. It can be seen that the insert deforms elastically until the external pressure reaches a magnitude of 50 MPa. Beyond this pressure, the insert deformed plastically. The calculation has to be stopped when the external pressure is beyond 75 MPa because convergence of the plastic simulations can no longer be achieved.

The above results are also similar to the reported in (Dillström, 2005) qualitatively in terms of stress magnitude, and distributions, and the patterns of plastic strain distributions. The final collapse load of 75 MPa is, however, smaller that that estimated in Dillström (2005). The most probable reason, as mentioned above, is the resolution requirements for iterations during the plastic strain calculation using the return-map algorithm to project the overestimated strain onto the yield function surface. The ADINA code applied in this analysis set a quite strict convergence criterion so more significant plastic flow generated by higher loading force cannot meet the convergence criterion. The commercial code applied in the calculations in Dillström (2005) may have more advanced plastic strain calculations for maintaining convergence of results with large plastic deformations so that larger collapse load may be obtained. Another reason, but perhaps a minor one, is the difference in the FEM models, such as mesh resolution and distribution.

Figure 40. Load-displacement curve results.
6. CONCLUDING REMARKS

The BEM 3D analysis of the canister design models show that with the maximum load of 44 MPa considered in the design premises, the cast iron insert is safe in terms of fracture initiation and growth, due to the dominance of compressive stress field, small magnitude of induced tensile stresses and adequate fracture toughness of the cast iron material.

The 2D FEM plastic analysis shows similar distribution patterns and magnitudes of stresses and plastic strains as reported in SKB literature, but a final collapse load of 75 MPa is reached, lower than that estimated in the SKB literature. The FEM analysis of collapse load considered in this report is the external load at the start of plastic collapse of the insert, not the full load for generating total buckling failure of the ligaments. Such buckling collapse of the insert may occur at a higher external pressure as indicated in SKB literature.
References


Dillström, P., Probabilistic analysis of canister inserts for spent nuclear fuel. SKB TR-05-19, 2005

Nilsson, F. Personal communication on canister insert’s toughness data, 2005.


Zhang, G. Personal communication on using ADINA, 2006.
## Appendix: Calculated SIF results

Table A1. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 1 mm, without deviation of fuel hole position).

Unit: MN/mm^{3/2}

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Table A5. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 1 mm, with fuel hole deviation of 1 mm).

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Unit: MN/mm$^{3/2}$
Table A6. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 1 mm, with fuel hole deviation of 2 mm).

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Unit: MN/mm\(^{3/2}\)
Table A7. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 1 mm, with fuel hole deviation of 5 mm).

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|---------|---------|---------|---------|---------|
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| 32 | 47 | -47.70102 | 1.119978 | -0.4886693 | 47 | -71.43544 | -0.4746824 | 0.2439178 |
| 33 | 48 | -46.49409 | 0.9865110 | -0.6227840 | 48 | -69.62212 | -0.4012598 | 0.3058269 |
| 34 | 49 | -46.16686 | 0.8210065 | -0.750632 | 49 | -69.12522 | -0.3105005 | 0.3638490 |
| 35 | 50 | -45.9629 | 0.6080514 | -0.828086 | 50 | -67.66778 | -0.2035011 | 0.3930323 |
| 36 | 51 | -44.71920 | 0.3793546 | -0.8862215 | 51 | -66.95003 | -0.0914393 | 0.4105914 |
| 37 | 52 | -44.51405 | 0.1426510 | -0.9183421 | 52 | -66.64001 | 0.02071259 | 0.4144561 |
| 38 | 53 | -44.61983 | -0.0994281 | -0.9254996 | 53 | -66.79595 | 0.1316442 | 0.4057776 |
| 39 | 54 | -44.51311 | -0.3323310 | -0.8925624 | 54 | -66.63637 | 0.2289074 | 0.3794693 |
| 40 | 55 | -44.71720 | -0.5521775 | -0.8375919 | 55 | -66.94259 | 0.3166784 | 0.3450675 |
| 41 | 56 | -45.19248 | -0.7572486 | -0.7606048 | 56 | -67.65353 | 0.3943608 | 0.3032781 |
| 42 | 57 | -46.16160 | -0.9412992 | -0.6694989 | 57 | -69.10804 | 0.4608998 | 0.2582096 |
| 43 | 58 | -46.48603 | -1.068176 | -0.5425384 | 58 | -69.59666 | 0.4978458 | 0.2045852 |
| 44 | 59 | -47.69707 | -1.169541 | -0.4115777 | 59 | -71.41799 | 0.5269722 | 0.1503601 |
| 45 | 60 | -49.82254 | -1.243595 | -0.2767526 | 60 | -74.60509 | 0.5468926 | 0.09542035 |
Table A8. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 1 mm, with fuel hole deviation of 10 mm).

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Unit: MN/mm$^{3/2}$
Table A9. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 2 mm, with fuel hole deviation of 1 mm).

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Unit: MN/mm$^{3/2}$
Table A10. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 2 mm, with fuel hole deviation of 2 mm).

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Table A11. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 2 mm, with fuel hole deviation of 5 mm).

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Unit: MN/mm$^{3/2}$
Table A12. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 2 mm, with fuel hole deviation of 10 mm).

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Table A13. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 5 mm, with fuel hole deviation of 1 mm).

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Table A16. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 5 mm, with fuel hole deviation of 10 mm).

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Unit: MN/mm$^{3/2}$
Table A17. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 10 mm, with fuel hole deviation of 1 mm).

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Unit: MN/mm$^{3/2}$
Table A18. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 10 mm, with fuel hole deviation of 2 mm).

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Table A19. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 10 mm, with fuel hole deviation of 5 mm).

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Table A20. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 10 mm, with fuel hole deviation of 10 mm).

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<td><strong>Crack 33</strong></td>
<td><strong>Crack 34</strong></td>
</tr>
<tr>
<td><strong>Crack 35</strong></td>
<td><strong>Crack 36</strong></td>
</tr>
<tr>
<td><strong>Crack 37</strong></td>
<td><strong>Crack 38</strong></td>
</tr>
<tr>
<td><strong>Crack 39</strong></td>
<td><strong>Crack 40</strong></td>
</tr>
<tr>
<td><strong>Crack 41</strong></td>
<td><strong>Crack 42</strong></td>
</tr>
<tr>
<td><strong>Crack 43</strong></td>
<td><strong>Crack 44</strong></td>
</tr>
<tr>
<td><strong>Crack 45</strong></td>
<td><strong>Crack 46</strong></td>
</tr>
</tbody>
</table>

The stress intensity factor (SIF) is calculated for different crack sizes and modes of fracture, with values given in MN/mm\(^{3/2}\). Each row represents a different crack instance, and the columns correspond to different modes of fracture (Mode I, Mode II, Mode III). The units used are MN/mm\(^{3/2}\).
Table A21. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 1 mm) for unevenly distributed confining pressure (loading) case a).

<table>
<thead>
<tr>
<th>MP</th>
<th>Mode I</th>
<th>Mode II</th>
<th>Mode III</th>
<th>MP</th>
<th>Mode I</th>
<th>Mode II</th>
<th>Mode III</th>
</tr>
</thead>
<tbody>
<tr>
<td>M87216</td>
<td>-565.8842</td>
<td>-0.068822</td>
<td>-0.850217</td>
<td>M87272</td>
<td>-510.0799</td>
<td>0.729183</td>
<td>1.970861</td>
</tr>
<tr>
<td>M87171</td>
<td>-538.0093</td>
<td>-0.379901</td>
<td>-0.877230</td>
<td>M87227</td>
<td>-486.5114</td>
<td>1.468451</td>
<td>1.971071</td>
</tr>
<tr>
<td>M87217</td>
<td>-521.4904</td>
<td>-0.706752</td>
<td>-0.875671</td>
<td>M87273</td>
<td>-472.1632</td>
<td>2.224555</td>
<td>1.900622</td>
</tr>
<tr>
<td>M87212</td>
<td>-514.0630</td>
<td>-1.057402</td>
<td>-0.849918</td>
<td>M87268</td>
<td>-465.9558</td>
<td>3.023774</td>
<td>1.769939</td>
</tr>
<tr>
<td>M87198</td>
<td>-501.0181</td>
<td>-1.328288</td>
<td>-0.705913</td>
<td>M87254</td>
<td>-454.0498</td>
<td>3.594273</td>
<td>1.387507</td>
</tr>
<tr>
<td>M87213</td>
<td>-494.4731</td>
<td>-1.549713</td>
<td>-0.519625</td>
<td>M87269</td>
<td>-448.0866</td>
<td>4.045057</td>
<td>0.8980159</td>
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<tr>
<td>M87214</td>
<td>-491.2011</td>
<td>-1.705870</td>
<td>-0.303185</td>
<td>M87270</td>
<td>-445.0605</td>
<td>4.328372</td>
<td>0.3441611</td>
</tr>
<tr>
<td>M87199</td>
<td>-491.7519</td>
<td>-1.794336</td>
<td>-0.062516</td>
<td>M87255</td>
<td>-445.5102</td>
<td>4.440379</td>
<td>-0.258887</td>
</tr>
<tr>
<td>M87188</td>
<td>-491.1769</td>
<td>-1.738002</td>
<td>0.1807702</td>
<td>M87244</td>
<td>-444.9808</td>
<td>4.193335</td>
<td>-0.852175</td>
</tr>
<tr>
<td>M87189</td>
<td>-494.4248</td>
<td>-1.612733</td>
<td>0.4030119</td>
<td>M87245</td>
<td>-448.1411</td>
<td>3.781450</td>
<td>-1.386118</td>
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<td>M87190</td>
<td>-500.9975</td>
<td>-1.421162</td>
<td>0.5985768</td>
<td>M87246</td>
<td>-454.2028</td>
<td>3.213985</td>
<td>-1.829165</td>
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<td>M87178</td>
<td>-513.9958</td>
<td>-1.177993</td>
<td>0.7542573</td>
<td>M87234</td>
<td>-465.6929</td>
<td>2.523613</td>
<td>-2.168557</td>
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<tr>
<td>M87179</td>
<td>-521.3788</td>
<td>-0.8467304</td>
<td>0.7962823</td>
<td>M87235</td>
<td>-472.3536</td>
<td>1.645017</td>
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<tr>
<td>M87180</td>
<td>-536.9498</td>
<td>-0.5347041</td>
<td>0.8147770</td>
<td>M87236</td>
<td>-486.4030</td>
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<td>-2.219000</td>
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<tr>
<td>M87181</td>
<td>-563.6142</td>
<td>-0.2362394</td>
<td>0.8041242</td>
<td>M87237</td>
<td>-510.0446</td>
<td>0.0243720</td>
<td>-2.148225</td>
</tr>
</tbody>
</table>

*MP: Mesh points

Figure A1. Location and labeling of mesh points (nodes) along the fracture tips for loading case a).
Table A22. Calculated stress intensity factor (SIF) at the crack tip (initial crack size of 1 mm) for unevenly distributed confining pressure (loading) case b).

<table>
<thead>
<tr>
<th>Crack 1</th>
<th>Crack 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>*MP</td>
<td>Mode I</td>
</tr>
<tr>
<td>M62406</td>
<td>-528.9605</td>
</tr>
<tr>
<td>M62361</td>
<td>-504.4506</td>
</tr>
<tr>
<td>M62407</td>
<td>-489.8394</td>
</tr>
<tr>
<td>M63560</td>
<td>-482.8420</td>
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<tr>
<td>M62403</td>
<td>-464.5686</td>
</tr>
<tr>
<td>M62378</td>
<td>-461.3539</td>
</tr>
</tbody>
</table>

*MP: Mesh points

Figure A2 Location and labling of the mesh points (nodes) along the fracture tips for loading case b).