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NUMERICAL SIMULATION OF LEAK TIGHTNESS UNDER DROP ACCIDENT CONDITIONS

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ABSTRACT

During the handling of transport and storage casks in the interim storage facility in Gorleben (Germany) different drop accident scenarios are possible.

In the storage configuration the containment system consists of the thick walled forged steel cask body with welded forged bottom and the tightness barriers with metallic gaskets. To guarantee the safe confinement of the radioactive inventory under hypothetical accident conditions the integrity of the cask body as well as the leak tightness of the gaskets can be demonstrated by using a numerical simulation.

A finite element analysis of the mechanical behaviour of the closure system under hypothetical accident conditions in the storage facility in Gorleben has been carried out exemplarily for a storage and transportation cask for vitrified high active waste. Different possible accident scenarios and the equivalent finite element models are introduced. The material models used for the cask and the ground as well as the boundary conditions are described. Finally suitable assessment criteria for integrity and leak tightness are discussed.

INTRODUCTION

In this work a drop of a transport and storage cask from the overhead crane during the handling in the interim storage facility in Gorleben is supposed. To guarantee the safe confinement of the radioactive inventory under these accident conditions the integrity of the cask body as well as the leak tightness of the gaskets can be demonstrated by using a numerical simulation. A finite element analysis of the structural behaviour of the closure system during the impact has been carried out exemplarily for a storage and transportation cask for vitrified high active waste. **Figure 1** shows a cask during the handling in the interim storage facility in Gorleben.

The following three drop accident scenarios are considered:

(i) Drop from upright position from a height of 3.465 m onto wooden shock absorber.
(ii) Drop from upright position from a height of 0.30 m onto the floor without shock absorber.
(iii) Drop from upright position from a height of 2.30 m onto the mounting rack.

For the finite element analysis a detailed 3D model with all relevant components of the cask as well as the floor of the interim storage facility is developed. For the different materials adequate material constitutive models have been chosen.

Figure 1. Cask during the handling in the interim storage facility in Gorleben

FEM-CODE

The analysis is performed by the FEM-code ABAQUS/Explicit [1] which is capable of solving highly nonlinear structural mechanics problems and complex contact problems. The code uses a central difference rule to integrate the equations of motion explicitly through time. The critical time increment is chosen automatically by defining a simplified stability limit which is calculated from the element length, and the wave speed of the material. ABAQUS/Explicit provides the required material constitutive models for metals, concrete and soils. For solving the contact problems a general contact algorithm is used. Contact constraints are enforced using a penalty contact method, which searches node-penetrations in the current configuration and applies the forces to oppose the penetration to the slave nodes while equal and opposite forces act on the master surface at the penetration point. The master surface contact forces are distributed to the nodes of the master surfaces. By default the contact stiffness (penalty stiffness), which relates the contact force to the penetration distance, is chosen automatically subject to the elastic material stiffness.

3D MODEL

The geometric discretization of cask and floor is performed by reduced integrated eight-node continuum brick type elements with linear shape function. Deformations caused by zero energy modes due to the reduced integration are prevented by applying an hourglass control procedure which adds artificial stiffness to the element.

The bolts of the lids are idealized by two-nodal beam elements with linear shape function.

The foundation of the interim storage facility in Gorleben is constructed with segmental concrete slabs above a 0.05 m thick blinding layer made of lean concrete. The size of one reinforced standard segment is 14.84 m x 16.70 m. For the finite element analysis a quadratic detail of the floor slab with the size of 10 m x 10 m is considered. The soil is taken into account for a depth of 2.50 m. The top soil is replaced by a compacted layer of sand, which is modelled by a change in density.

With respect to symmetry only a quarter of the system is analyzed. On the plane of symmetry the boundary conditions are given by the symmetry, on the opposite boundaries the horizontal degrees of freedom of the solid nodes of the soil are restricted. The vertical degrees of freedom of the concrete slab and all three degrees of freedom of the bottom of the model are restricted. The 3D-model is shown in **figure 2**. For simulation of the drop on the mounting rack the model has to be extended to a half model.

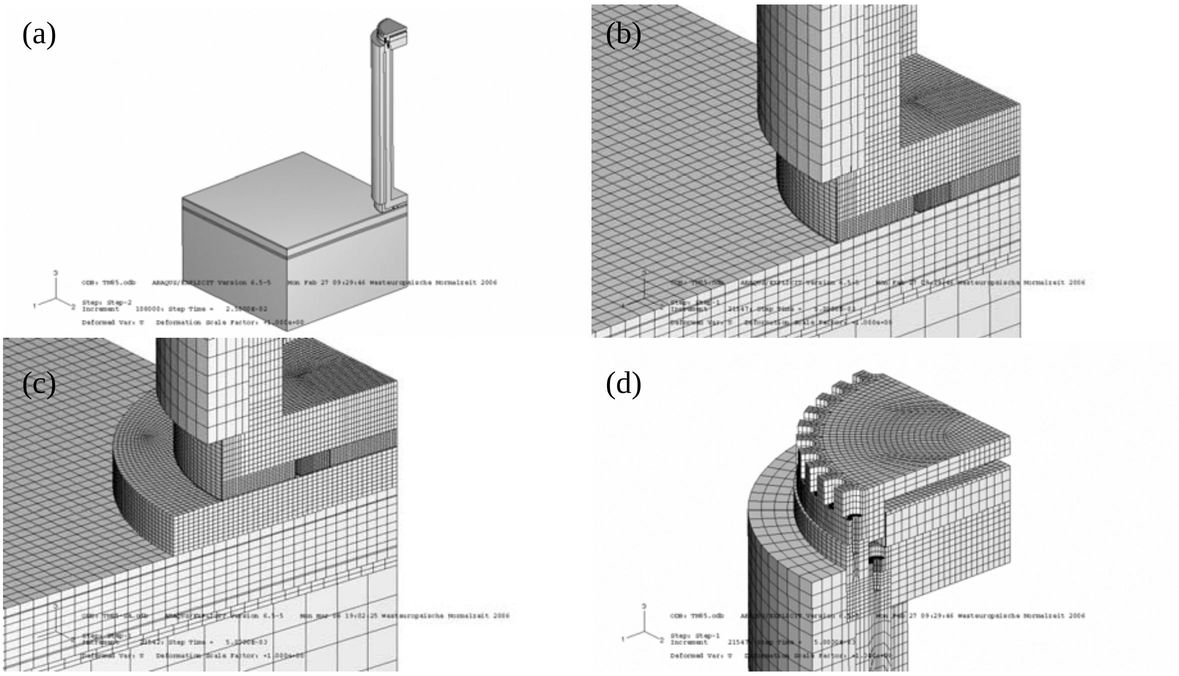

Figure 2. Finite element mesh: (a) Quarter model (b) Bottom of the cask (c) Bottom of the cask with shock absorber (d) Primary and secondary lid

LOAD

Pretension of the bolts

To simulate the pretension of the bolts a thermal load is applied to the beam elements. To avoid radial compressive forces the bolt is connected to the cask body at the screw thread by imposing a kinematic coupling constraint only in axial direction. The axial motion of the top end of the bolt is coupled to the upper surface of the washer. The thermal load is chosen by assuming a thermal expansion coefficient of $15\cdot10^{-6}$ K^{-1} and adjusting the temperature difference to obtain the correct value of pretension.

Drop from a height of 3.465 m onto shock absorber

The position of the cask is directly above the wooden shock absorber. The thickness of the shock absorber is 0.20 m so the effective drop height is 3.265 m. According to the impact speed an initial translational velocity of 8.00 m/s is applied to the nodes of the cask.

Drop from a height of 0.30 m onto the floor

The cask is located above the floor slab. The calculation starts with a initial translational velocity of 2.43 m/s at the nodes of the cask.

MATERIAL CONSTITUTIVE MODELS AND MATERIAL PROPERTIES

The chosen material constitutive models are verified by experimental results in [2]. In this publication a calculation of a real drop-test is performed and accelerations as well as strains are compared to the experimental results at selected measuring points.

Cask body, primary and secondary lid

The cask as well as the lids consist of forged steel, for which elastoplastic material behaviour with isotropic hardening is assumed. The material model uses von Mises yield surfaces with associated plastic flow. The uniaxial stress-strain response follows a linear elastic relationship given by young's modulus until yield stress is reached. The plastic strain hardening is given by a hardening modulus, so the assumed material behaviour is bilinear. Plastification occurs at the screw threads due to the simplifications in the model. Besides that no other plastification occurs. Since tightening of the bolts is a quasi-static process rate-dependent effects are not important.

Shock absorber

The characteristic of the shock absorber is given by the one-dimensional stress-deformation-relationship. Since the behaviour after rebound is not of interest a hyperelastic constitutive material law is used.

Floor slab

ABAQUS/Explicit provides a concrete damaged plasticity model which is used to model the floor slab. This model represents the inelastic behaviour of reinforced and unreinforced concrete under monotonic, cyclic, and dynamic loading using concepts of isotropic damaged elasticity in combination with isotropic tensile and compressive plasticity.

Under uniaxial load the response is linear up to failure stress under tension, which corresponds to initial microcracking and up to initial yield under compression respectively.

In tension the postfailure stress is a function of cracking displacement and depends on the fracture energy which is defined as the energy required to open a unit area of crack [3]. In compression the uniaxial response is characterized by stress hardening followed by strain softening in the plastic regime.

The model uses a modified Lubliner [1, 4] yield surface. The flow potential is the Drucker-Prager hyperbolic function that ensures that the flow direction is always uniquely defined. Plastic flow is non-associated.

Reinforcing steel

For the reinforcing steel elastoplastic material behaviour with isotropic hardening and von Mises yield surfaces is assumed. The uniaxial response is characterized by young's modulus, yield stress and the true strain at the uniform elongation. Beyond this point perfect plasticity is assumed. In the model layers of reinforcement are defined by a set of surface elements which are embedded in a set of host continuum elements.

Soil

For the sandy soil an extended Drucker-Prager model is chosen. The yield surface is identical to the linear Drucker-Prager yield surface in the meridian plane which is characterized by the cohesion and the friction angle of the material. In the deviatoric plane the description of the Drucker-Prager yield surface is modified by introducing a form factor *K*, which gives the ratio of the yield stress in triaxial tension to the yield stress in triaxial compression. In this calculation the form factor is assumed to be 0.778 which is the limit to ensure a convex shape of the yield surface. This choice also shows a good agreement to the yield surface of Lade [5] which is generally accepted for modelling sandy soils in geotechnical applications.

Compared to the original Drucker-Prager model the yield role of the extended Drucker-Prager model is non-associated. For this calculation the dilatation angle is chosen to be zero. Since no hardening is taken into account the material is assumed to be perfectly plastic.

The rate dependency is taken into account by an increase of young's modulus. Referred to [6] the dynamic Young`s modulus is in the range of 200 to 500 N/mm². Conservatively the upper bound of 500 N/mm² is chosen for the calculation.

RESULTS

The following criteria are consulted for the assessment of leak tightness:

(i) The gap between the lid and the cask body is of the magnitude of the roughness depth of the sealing faces. (ca. 4 µm to 8 µm)
(ii) The gap between the lid and the cask body is considerably less than the tolerance of groove depth (100 µm).
(iii) The gap between the lid and the cask body is less than the usable elastic springback of the metallic gaskets.
(iv) The metal-to-metal contact is essentially preserved.
(v) Pretension of the bolts remains complete.

Leak tightness after a drop from a height of 3.465 m

Neither primary nor secondary lid lift off thus the metal-to-metal contact remains completely closed during the impact. There is no significant gap between the lids and the cask body. **Figure 3** shows the bolt forces during the impact.

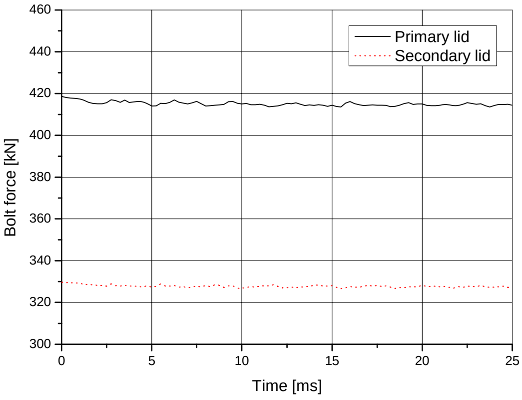

Figure 3. Drop from a height of 3.465. Bolt force

Leak tightness after a drop from a height of 0.30 m

The flexural mode dominates the response of the lids. The lids do not lift off completely so that the metal-to-metal contact is essentially preserved. The gap between the lid and the cask body in the area of gasket is limited to 35 μm for the first amplitude of the oscillation. Subsequent amplitudes are of the magnitude of 10 μm or below (**figure 4**). The rebound height is limited to 30 mm so that the second impact after rebound remains unconsidered. The deformed shape at the time of highest amplitudes is shown in **figure 5**.

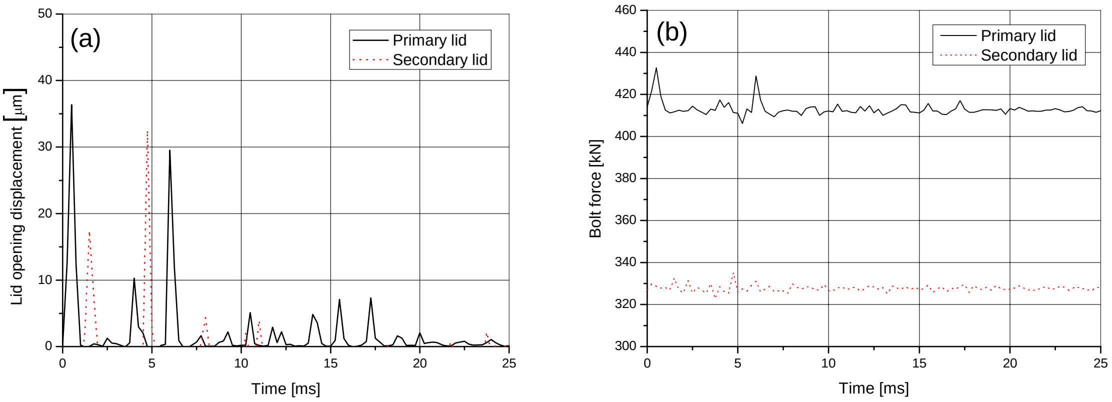

Figure 4. Drop from a height of 0.30 m. (a) Lid opening displacement (b) Bolt force

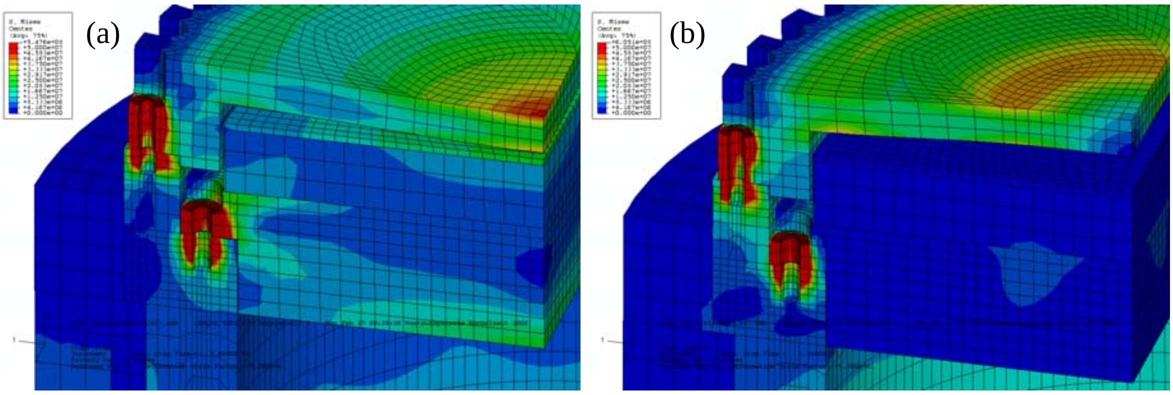

Figure 5. Drop from a height of 0.30 m: v. Mises stress and deformed shape (scale factor: 50) (a) 0.5 ms (b) 1.5 ms

Leak tightness after a drop from a height of 2.30 m onto the mounting rack

In this supposed accident scenario the cask is configured without secondary lid. Hence only the primary lid is important for assessment of the leak tightness. The primary lid does not lift off completely. The metal-to-metal contact is essentially preserved. The gap between the primary lid and the cask body is limited to 22 μm for the first amplitude of the oscillation. Subsequent amplitudes are of the magnitude of 10 μm or below (**figure 6**).

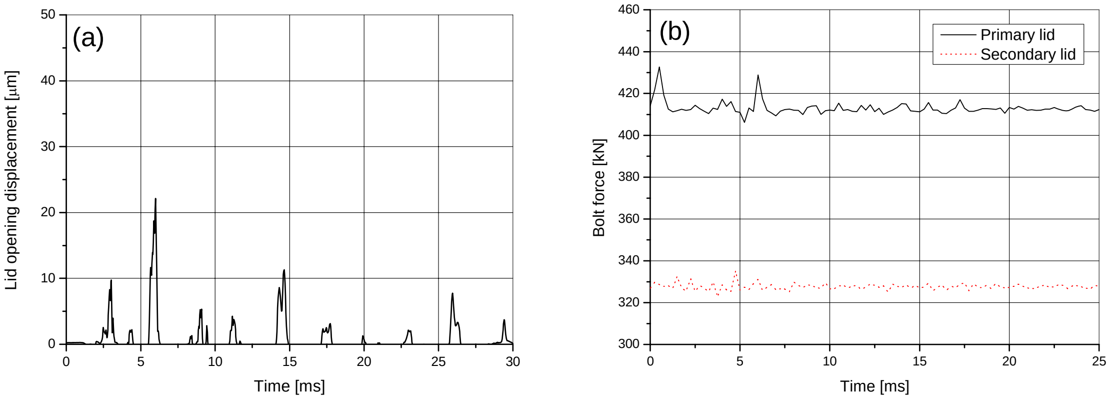

Figure 6. Drop from a height of 2.30 m. (a) Lid opening displacement (b) Bolt force

CONCLUSIONS

In all considered cases the metal-to-metal contact is essentially preserved. The flexural oscillation of the lids results in marginal gaps between the lids and the cask body with a limited number of peaks in the area of the gasket. Hence it is to assume that no relevant displacement occurs between the metallic gaskets and the groove and respectively the sealing face.

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