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FRACTURE MECHANICAL ANALYSIS OF A CYLINDRICAL CAST IRON CASK

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ABSTRACT
The safety evaluation of cask components made of ductile cast iron includes investigations to prevent brittle fracture. Generally, ductile cast iron is endangered by brittle fracture especially at low temperatures (down to -40°C) and in combination with existing crack-like material defects. An applicable method is the assessment of fracture resistance using fracture mechanics according to the IAEA guidelines. The approach is based on the prevention of fracture initiation. For application of these principles for drop loads, account must be taken both of dynamic stresses within the component and dynamic material behavior. Basically, the dynamic stress intensity factor of postulated pre-existing crack-like defects is compared with the dynamic fracture toughness of the material. Applicable numerical and experimental methods for the safety assessment of cask components are demonstrated for the case of an artificially pre-cracked cylindrical cast iron cask which undergoes dynamic loading conditions as result of the hard impact between the cask and a concrete target. The proposed evaluation procedure is a combination of numerical and experimental steps. Exemplarily, the calculated stress intensity factor is compared with measured fracture toughness values from single edge notched bending specimens.

INTRODUCTION
For the safety evaluation of transport and storage casks for radioactive materials made of ductile cast iron it should be demonstrated that inadmissible plastic deformations especially in the region of the lid system and failure by fracture can be excluded. Generally, ductile cast iron is endangered by brittle fracture especially at low temperatures (down to -40°C) and in combination with existing crack-like material defects. To prevent failure by fracture, the advisory material [1] to the IAEA regulations [2] describes the applicable fracture mechanics safety concepts. There are also guidelines [3] based on fracture mechanics principles especially for the application of ductile cast iron (DCI) for transport and storage casks for radioactive materials. All approaches are based on the prevention of fracture initiation. The fracture mechanical resistance of a cask is usually demonstrated under most unfavorable drop test conditions. In the following the case is investigated when a cylindrical DCI cask with an existing crack-like material defect in the area of maximum stresses hits a hard concrete target. Such dynamic load

conditions require that the evaluation procedure considers both dynamic stresses and dynamic material behavior.

REQUIREMENTS

The mechanical requirements both for transport casks according to the transport regulations [2] as well as for disposal canisters according to the acceptance criteria for final disposal in the German KONRAD repository [4, 5] are specified decisively by drop tests with the cask. Here the fracture mechanical analysis is demonstrated exemplarily using a prototype cask for final disposal. These casks are grouped according to the KONRAD waste container classes (ABK) dependent on the intended radioactive content. Casks of class I (ABK I) have to withstand a vehicle impact with velocity up to 4 m/s or equivalently a drop from a height of 0.8 m. Accidental loads are covered for class II (ABK II) - containers by a drop test from a height of 5 m onto a defined concrete target representing the most unfavorable conditions of the container acceptance area and the hard rock ground of the KONRAD repository.

The drop height results from the assignment to a waste container class plus an increase as compensation for the greater potential energy of a loaded cask if the drop test is conducted with an empty cask. The selected drop test position should maximize cask stresses and is therefore strongly dependent on the cask design. Typically, several drop test positions have to be analyzed. For cylindrical casks the horizontal drop is preferred if the maximum hoop stress of the cask body is of primary interest. The test temperature is given as -20 °C by the KONRAD repository acceptance criteria [4, 5].

Concerning the drop test target it is required that i) the target is a concrete foundation, ii) the compressive strength of the target material has to fulfil at least the properties of the former German concrete grade B35 [6], iii) the influence of the foundation soil is negligible, and iv) the foundation is neither destroyed nor moved. Finally the representative target is a prefabricated concrete slab clamped in a steel frame and joined with grout to the IAEA target [1] of the BAM drop test facility or another qualified IAEA target. In practice the specification of the former concrete grade B35 may be challenging because suppliers manufacture no longer according to the obsolete specification. Instead the new concrete grade C30/37 [7] is provided. To meet the minimum requirements of the concrete foundation on the one hand and to not load the cask unnecessarily strongly on the other hand, the concrete grade is defined in more detail by the cube compressive strength after 28 days: lowest single value $\beta_{WN} \geq 35$ MPa, mean value $\beta_{WS} \geq 40$ MPa. By the specified compressive strength after 28 days it is guaranteed that the concrete fulfils at least the requirements to a concrete of former grade B35.

The dimensions of the concrete slab have to be chosen in a way that at the flat drop a cubic cask hits the slab in a distance from its edges greater than the slab thickness. In case of a horizontal drop of a cylindrical cask this condition must be met at both ends of the cask and defines the minimum edge length of a preferably square target area. Additionally the concrete slab must be reinforced adequately.

ASSESSMENT PROCEDURE

For the exclusion of inadmissible plastic deformations a dynamic stress analysis of the flawless cask or component has to be carried out. Existing safety assessment concepts [2, 3] assume that such kind of safety demonstrations can be performed experimentally or numerically or in combination of both methods. Numerous drop tests have shown that the test object hits the target hardly ever under ideal conditions and that already a small impact angle typically reduces the expected cask load. This leads to the consequence that a numerical simulation of the drop test scenario under ideal conditions is necessary to validate the maximum cask load. The exclusion of inadmissible plastic deformations is successful if the dynamic equivalent (von Mises) stress remains below the dynamic yield stress of the material. At exceedance of the yield point and consequently existence of permanent deformations the affected parts of the cask should be subjected to a detailed analysis considering the triaxiality of the stress state and the kind of loading (tension or compression). Small plastic deformations may be admissible if the safety objectives of the cask like integrity and leak-tightness remain fulfilled.

For the exclusion of failure by fracture a dynamic fracture mechanical analysis of postulated material defects of the cask or component material has to be carried out subject to the test requirements. The size of material defects to be considered for the fracture mechanics safety assessment depends on the acceptance criteria for the later serial production and is usually verified at each cask by non-destructive, typically ultrasonic inspection. Concurring with the IAEA recommendations [1] crack initiation is not allowed. This means analytical and numerical analyses have to be performed to define and evaluate the most unfavorable test conditions for prototype casks to provide a complete safety demonstration against crack initiation and the potential loss of cask integrity.

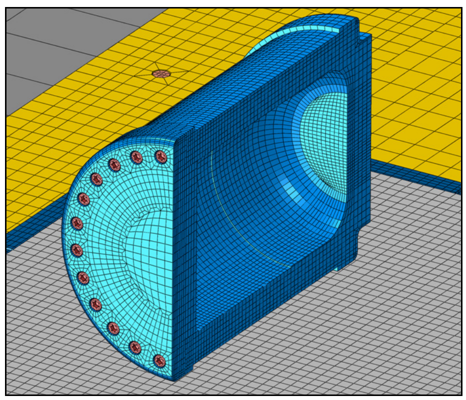

Figure 1. Finite element analysis of the drop test scenario

As a first step a numerical simulation of the test scenario to determine highest stresses to be expected for the cask without any flaws and with realistic material models should be carried out. Fig. 1 shows the finite element model of the test scenario with cylindrical cask and concrete target. The cask model includes a detailed meshed lid with screws. If necessary, dynamic material properties dependent on temperature and strain rate should be considered. From the calculation results, the locations of high major principal stresses in the structure can be found. At these locations also a high fracture mechanical load of crack-like defects has to be expected. A postulated crack has to be located there in a way that a normal stress is acting on the crack faces. The size of postulated crack-like defects depends on the requirements for non-destructive testing as mentioned above. The number of similar crack configurations to investigate can be reduced by the restriction to cases with highest stresses. The dynamic crack tip parameter is calculated by means of a dynamic numerical simulation of the cask (or cask component) containing the reference crack. Additional safety factors must be considered in this procedure to cover uncertainties.

CASK MATERIAL

Within a research project [8] a specific test cask was manufactured of a ductile cast iron with minimum admissible material properties concerning later standards for serial production. Complying with the standard specification [9] fracture mechanics SE(B)50 specimen of this material provided a valid initiation fracture toughness of 49 MPa√m at a temperature of -40 °C and a loading rate of $2.1 \cdot 10^3$ MPa√m/s [8].

The size of tolerable material defects results from the acceptable fracture mechanical load of the defect dependent on the material fracture toughness, stress load, defect shape, position in the structure and kind of load. In addition, the defect must be detectable by non-destructive testing. In this sense a notch was designed as an artificial crack-like material defect and machined into the test cask [8]. The material of the test cask was characterized by a statistical evaluation of 29 three-point bend specimens SENB10 because of the limited number of test results from SE(B)50 specimens. The loading rate dK/dt was in the range of $2.4\cdot10^4$ to $3.0\cdot10^4$ MPa√m/s. The test temperature was -20 °C corresponding to the KONRAD repository acceptance criteria [4, 5]. The fracture mechanical measurements were carried out according to the J-integral concept. Unfortunately, crack growth resistance curves could not be determined because most specimens showed local instabilities, so-called pop-ins. As an alternative, the initiation fracture toughness [10, 11]

$$J_{dUC} = \frac{2U}{B_N (W_N - a_0)} \tag{1}$$

with the dissipated impact energy U till the local instability, specimen thickness B_N, specimen width W_N and fatigue crack length a_0 was identified which is considered as independent of the specimen geometry. Then a characteristic dynamic initiation fracture toughness $K_{Id}(J_{dUC})$ of 49 MPa√m was derived from the J_{dUC}-values which yields with a safety factor of 1.3 a design value of 37.7 MPa√m [8].

CRACK-LIKE MATERIAL DEFECT

A semi-elliptical surface crack was assumed as most critical material defect according to the IAEA advisory material [1]. The stress distribution inside the cask wall results from the numerical simulation of the test scenario without material defects. From the linearized stress distribution, the crack configuration with a semi-axial ratio a/c of 1/3 and the design value of the initiation fracture toughness, a notch depth a of 18 mm and notch length 2c of 108 mm were derived.

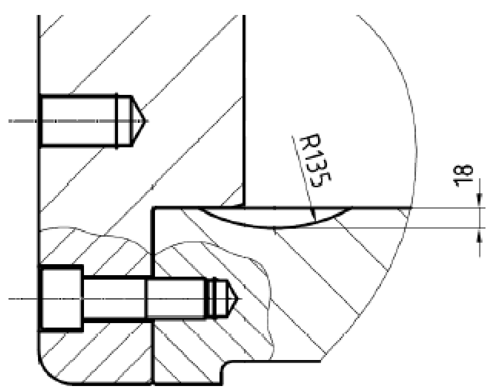

Figure 2. Notch in the cask wall near the lid [12]

The notch was machined with a milling cutter and had the shape of a segment of a circle as illustrated in Fig. 2. Therefore, the notch length was 135 mm with the given notch depth of 18 mm. The resulting depth-length-ratio $a/2c$ = 1/7.5 is conservatively smaller than the aspect ratio of 1/6 according to the IAEA recommendations [1]. Besides, the notch was moved by 27 mm in direction of the cask center to be safely away from the top rim of the cask shaft.

DROP TEST

For the drop test a cylindrical test cask was manufactured within a research project [8] and provided with a notch as specified above. The cask had a gross weight of 5.1 Mg, an outer diameter of 1060 mm, a height of 1500 mm, and a shaft diameter of 750 mm. The wall thickness between cask lid and bottom was reduced by 20 mm. Hence, a wall thickness of 135 mm arises. The cask body did not show any compulsory registrable material defects in the non-destructive testing.

At first, the cask was instrumented with strain gauges and accelerometers. Then, the cask was cooled with liquid nitrogen inside an enclosure. During the following drop test the empty cask equipped with the notch impacted horizontally a concrete target from a height of 0.96 m and at a temperature of -20 °C according to the KONRAD repository acceptance criteria [4, 5]. Fig. 3 illustrates the situation after the drop test.

Figure 3. Cylindrical DCI cask after drop test from 0.96 m height onto a concrete target

The accelerometer data showed that the cask has hit almost horizontally. The visual inspection did not show any noticeable indications. A permanent ovalization of the cask body was not found. The concrete foundation was not damaged and no cracks occurred in the concrete slab. Small imprints with a depth of some millimeters due to the overhanging cask lid and bottom were found, but are permitted.

FRACTURE MECHANICAL ANALYSIS

The finite element model in Fig. 1 was used for the numerical fracture mechanical analysis. Initially calculated and measured strains were compared. Fig. 4 shows the results for the measuring point at the 6-o'clock-position in a distance of 300 mm from the top rim of the cask shaft. This position is 125 mm away from and in line with the notch.

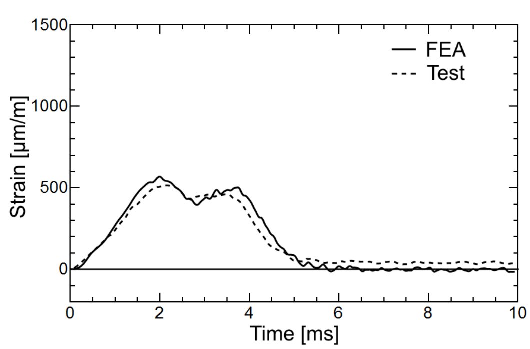

Figure 4. Hoop strain at the 6-o'clock-position in a distance of 300 mm from the top rim of the cask shaft

A good correspondence of both curves can be seen. Other measuring points show a comparable correspondence between FEA and test results. Hence, the fracture mechanical analysis can be done with confidence on the basis of the results from the finite element simulation.
To calculate the stress intensity factor, the formula for a semi-elliptical surface crack in longitudinal direction inside a hollow cylinder was used [13]. The dynamic stress at the position of the notch was inserted in the formula as bending stress. This methodology is explained by Zencker [14].
The calculated history of the stress intensity factor is shown in Fig. 5. A maximum stress intensity factor of 34.1 MPa√m was estimated from these calculations, which is 10 % smaller than the design value of 37.7 MPa√m [8]. Consequently, under the given test conditions the crack-like material defect was loaded sub-critically, i.e. a crack initiation was not to be expected.

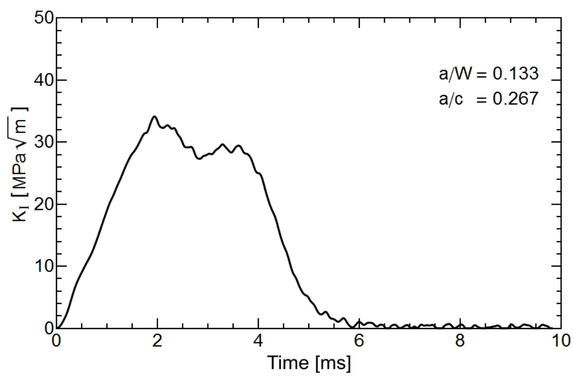

Figure 5. Stress intensity factor of the crack-like material defect

Micro-sections at three different positions in length direction of the notch were part of the post-test examination. The micrographs showed that the radius at the notch root was clearly below the intended maximum value of 0.1 mm and no crack initiation was found [8]. In this way it could be shown that the fracture mechanical safety of cask components made of ductile cast iron can be demonstrated with the presented assessment procedure.

SUMMARY

Ductile cast iron is endangered by brittle fracture especially at low temperatures (down to -40°C) and in combination with existing crack-like material defects. It has to be shown for casks made of ductile cast iron that they meet the safety requirements also under these conditions. Inadmissible plastic deformations have to be excluded. Failure by fracture must be prevented. The fracture resistance can be assessed by postulation of crack-like material defects and application of the methods of fracture mechanics.
The application of this concept was demonstrated exemplarily with a cylindrical DCI cask, which had to withstand a drop from a height of 0.96 m onto a hard concrete target at a temperature of -20 °C. The assessment procedure is a combination of numerical calculations and experimental tests. The dynamic initiation fracture toughness of the cask material was measured separately by fracture mechanical standard test methods. An artificial crack-like material defect was considered, representing maximum acceptable material defect dimensions, which can be reliably detected by standard methods of non-destructive testing. Finally, the fracture mechanical safety of the cask design including an artificial crack-like material defect could be demonstrated by showing no crack initiation under the given test conditions. In this way the assessment procedure was also validated.

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