MECHANICAL SAFETY ANALYSES OF CAST IRON CONTAINERS FOR THE KONRAD REPOSITORY

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ABSTRACT

Within the last years BAM has carried out numerous drop tests with prototype casks made of ductile cast iron onto targets according to the requirements for final disposal of non-heat generating waste in the German KONRAD repository. The results have shown that the target specifications in the acceptance criteria have to be defined more accurately to get reproducible test results with high precision. Hence, a suitable test stand foundation was developed with much effort. The integrity of the upper concrete layer of this target must be preserved during a test.

Recently the geometrical properties of a tested cubic cast iron container led to a concentration of the impact forces beneath the container walls. The target was damaged strongly with the consequence of inadmissible reduction of cask stresses. For that reason the target construction was modified. However, the basic design was not changed. A prefabricated concrete slab was still joined by a mortar layer to the IAEA target of the BAM drop test facility. In the course of the optimization of the test stand foundation the concrete slab dimensions and the reinforcement were enlarged. During the drop test repetition the target kept intact. Additionally, the mechanical behavior of the cast iron container and the target was analyzed by finite element calculations.

This improved target construction is suggested as a reference target for drop tests with casks whose mass and base area are covered by the container types VI or VII respectively according to the KONRAD repository acceptance criteria.

The measurements during the drop tests with cast iron casks have provided the strains on the cask surface at selected positions. This allows the verification of finite element simulations of drop tests which show the stress distribution also inside the component. In September 2008 a drop test was carried out with a cylindrical cast iron cask containing an artificial material defect which was designed under consideration of critical stress states in the cask body. This drop test could demonstrate the safety against failure by fracture of a cask made of a special cast iron with reduced fracture toughness.

INTRODUCTION

Metallic recycling material from decommissioned and dismantled nuclear installations is reusable to some extent for production of ductile cast iron (DCI). Transport and storage casks for radioactive materials can be manufactured from such new ductile cast iron grades (called GJS/R) if it can be proved that they fulfill the safety requirements. Starting out from the failure behavior of these DCI grades it was investigated in the research project “Development of assessment methods for transport and storage containers made of ductile iron with increased contents of metallic recycling material (EBER)" [1, 2, 3], whether unavoidable material defects from the manufacturing process can be permissible in safety relevant components. Applied to transport and storage casks the material would be used in the brittle-ductile transition range. Therefore, fracture mechanical assessment methods are the predominant evaluation procedure. Their application requires precise knowledge of dynamical stress states in cask structures.

In the project numerous drop tests were carried out with cask-like components as well as prototype casks onto targets according to the acceptance criteria for final disposal in the German KONRAD repository [4, 5] with the use of GJS/R as more economical alternative material for final storage casks in mind. All castings were made available from the research project "Optimization of scrap metal recycling (FORM)" [6, 7] by the German foundry Siempelkamp Gießerei which was supported by German ministry BMBF under contract No. 02 S 8011. The drop tests have shown that the test specifications are not sufficient to obtain reproducible test results with the needed accuracy. Therefore, a test stand foundation representative of the ground in the KONRAD repository with a very detailed specification was developed with much effort [1, 2]. In routine use an inadmissible damage of this target construction occurred with very heavy test objects in combination with line loads (contrary to distributed loads in many other cases). Consequently, the target construction was improved for use with test objects up to the gross weight of 20 Mg. The suitability of the reinforced target as representative of the KONRAD hard rock ground was shown with an additional drop test. This improved target construction is suggested as a reference target for drop tests according to the KONRAD repository acceptance criteria with casks whose mass and base area are covered by the container types VI or VII respectively.

The measurements from drop tests with cylindrical and cubic cast iron casks provide the strains on the cask surface at selected positions. This allows the verification of finite element simulations of drop tests which show the stress distribution also inside the component. In September 2008 a drop test was carried out with a cylindrical cast iron cask containing an artificial material defect which was designed under consideration of critical stress states in the cask body. This drop test could demonstrate the safety against failure by fracture of a cask made of a special cast iron with reduced fracture toughness according to the KONRAD waste container class (ABK) I.

FRACTURE MECHANICAL INVESTIGATION OF CYLINDRICAL DCI CASKS

Failure by fracture can be caused by unavoidable material defects from manufacturing which were not detected in non-destructive testing. Therefore, the question must be answered, what material defect sizes can be accepted for safety-relevant applications. According to the usual fracture mechanical assessment concepts [8, 9] crack initiation is not permitted, i.e. the fracture mechanical load must always be smaller than the material resistance to crack initiation (here the dynamic fracture toughness).

The development of new DCI grades was carried out in the project FORM [6]. Initially special castings reached only small dynamic fracture toughness values in the range of 22…27 MPa√m measured with fracture mechanical standard procedures [7]. In 2005 drop tests with artificially pre-cracked components and prototype casks have shown the application limits of the material in those days [3]. Meanwhile the fracture mechanical properties of GJS/R were improved substantially by efforts in the project FORM [10]. Dynamic fracture toughness values up to 48 MPa√m could be measured of specimens from special castings for the process optimization. The applicability of the improved material as cask material was investigated once more in a drop test in 2008.

Figure 1. Drop test with DCI cask GB FORM III-2007

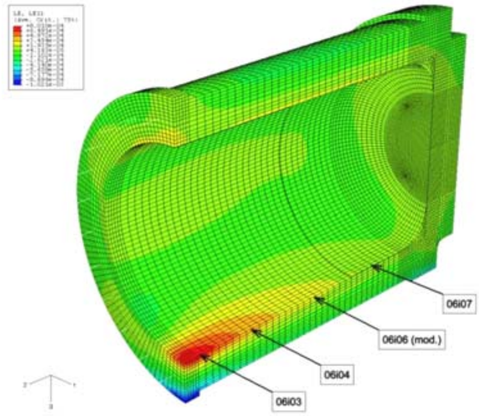

Figure 2. Circumferential strain inside the cylindrical cask for horizontal drop from 0.96 m height

The experimental set-up is shown in Fig. 1. The test cask has to withstand an impact with velocity of 4 m/s or a drop from 0.8 m height onto the representative target without loss of cask integrity according to KONRAD waste container class (ABK) I. The drop height was increased to 0.96 m to account for the missing contents. The test cask was cooled down to -20 °C. It had a gross weight of 5.1 Mg, length of 1,500 mm, and an outer diameter of 1,060 mm. The cask wall was 10 mm thinner between lid and bottom end which lead to point loads at the cask ends, i.e. there is no line load which would be typical for a horizontal drop scenario. This constructive feature should optimize the stress distribution inside the cask structure. At the first drop test with such a cask in 2005 the maximum stress was expected in the middle of the impacting cask wall at the inner surface where a notch as artificial material defect was machined. Contrary to this prediction, a precise test simulation localized the position of highest first principal stress near the cask lid (Fig. 2). The cause for this discrepancy is the small gap between lid and cask body which allows a larger ovalization of the cask body at the lid end and may not be neglected. In 2007 an additional test of a cask without artificial defects was carried out for experimental validation of the calculated stress state.

The value (195 MPa) and position of maximum stress in the cask structure were known from previous drop tests. The cask manufacturer derived the depth of an artificial notch by means of the known dynamic fracture toughness of the used material and a safety factor. Then a notch with depth of 18 mm was machined at the expected position with highest stress to demonstrate the safety against fracture of a prototype cask made of ductile iron with increased contents of metallic recycling material (Fig. 3). The notch is usually considered as a sharp crack in such fracture mechanical calculations for a failure safe design. The machining of the notch is of special importance to be able to presuppose a crack-like defect. An effortful mechanical process was used to guarantee that the radius of notch tip is smaller than 0.1 mm at an opening angle of 60°. Comparative investigations for ductile cast iron have shown that under these conditions the fracture toughness in a component is not higher than in a pre-cracked laboratory specimen. The artificial material defect has the shape of a segment of a circle due to the machining process.

Figure 3. Notch with strain gauges

The cylindrical cast iron cask was equipped with 36 strain gauges on cask wall and lid as well as 2 accelerometers at the top to record the course of the test in detail. It can be concluded from the accelerometer measurements that the cask hit the target almost flatly. Specimens were taken after the test from the region around the notch tip to examine possible crack initiation by microscopy as part of the FORM project. Any crack initiation was not found [10].

REFERENCE TARGET

Besides cylindrical casks also cubic cast iron containers made of GJS/R were tested according to the acceptance criteria for final disposal in the KONRAD repository [4, 5]. Test containers similar to the KONRAD container types VI and VII with outer dimensions 1,600 mm x 2,000 mm x 1,450 mm with special features for stress optimization like larger fillets and a 10 mm thick ledge surrounding the container bottom were developed in the project FORM. Such a container with wall thickness of 160 mm and without contents has a mass of approximately 16.2 Mg. It should fulfill the requirements according to the KONRAD waste container class II, i.e. the container integrity must be preserved during a drop test without impact limiters from 5 m height onto a target representative of the ground in the repository. The drop height was corrected also in this case as compensation for the missing contents. The impact velocity is 10.44 m/s for a given drop height of 5.55 m (Fig. 4).

Figure 4. Drop test with DCI container GC FORM III-2007

The target representative of the ground in the repository is a prefabricated concrete slab clamped in a steel frame and joined to the IAEA target [8] of the BAM drop test facility. After numerous tests with different materials it was decided to use a mortar layer to connect the concrete slab with the surface of the IAEA target [1]. According to the KONRAD acceptance criteria the compressive strength of the concrete slab has to fulfill at least the properties of the former German grade B35 [11]. Additionally the target construction must preserve its integrity because horizontal forces would be bound by the virtually infinite rock in the repository and the ground should remain intact apart from local plastic deformation. The concrete slab originally used for both cask types had the dimensions 2.40 m x 2.80 m x 0.30 m. In routine use of this target construction an inadmissible damage of the slab and the mortar layer occurred especially for high line loads near the edges of the slab. Vertical cracks inside the slab and the strongly destroyed mortar layer near the edges indicated the loss of integrity of the target construction (Fig. 5). High speed video illustrates impressively the distinctive horizontal displacements of slab and steel frame during the impact.

The larger energy absorption due to a broken foundation leads to an inadmissible reduction of the load of the container. Therefore, the target construction was optimized in the preliminary stages of a drop test with a cubic container with bottom ledge and expected high line loads near the edges of the slab. The basic design was not changed. In the first step of the optimization of the representative target the dimensions were enlarged to 3.00 m x 3.40 m x 0.40 m. The information of the manufacturer of the concrete slab about the avoidance of special transport measures were taken into account here and limited the slab dimensions. In another step the reinforcement was increased from 0.7 % to nearly 1.6 %. The design of the reinforcement ensued on the basis of the decelerations measured at earlier drop tests. Special attention was paid to the arrangement and anchoring of the reinforcement bars. The minimum thickness of the concrete layer on top of the reinforcement grid was 5 cm to allow undisturbed local plastic deformation on the surface of the slab. The thicker steel

Figure 5. Destroyed mortar layer after drop test with DCI container

Figure 6. Mortar layer after drop test with optimized target construction

frame was strengthened additionally with fins. It is assumed, however, that the steel frame is not able to bound considerable horizontal forces or to prevent cracks in the concrete slab because of its limited stiffness compared to the slab.

Already the high speed video of the repeated drop test of the container with bottom ledge showed the influence of the strengthened target construction. The horizontal displacement of the edges of the slab remained small. The jump height of the container multiplied. Small plastic imprints occurred only along the lines of contact. The mortar layer remained almost intact (Fig. 6). The substantial measured strains on the container surface have increased by 15 % for the modified target. Figure 7 shows exemplarily the history of measured strain on the surface of a fillet at the container bottom. The maximum strain during the primary impact has increased by 40 % at this position. It is obvious that the target construction has to be adapted to the actual mass, geometry and drop height of the test container.

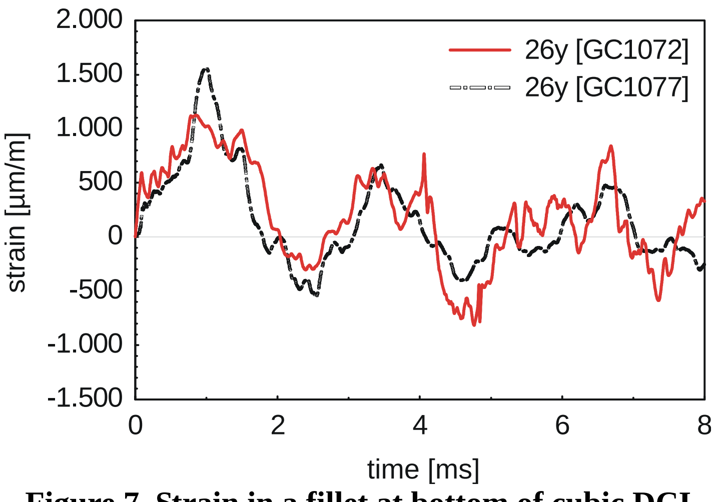

Figure 7. Strain in a fillet at bottom of cubic DCI container before (GC 1072) and after (GC 1077) optimization of target construction

The improved target construction is suggested as a reference target for drop tests with casks whose mass and base area are covered by the container types VI or VII respectively according to the KONRAD repository acceptance criteria [4, 5].

STRESS ANALYSIS

The test objects were equipped extensively with strain gauges and accelerometers at the drop tests carried out in the project. The kinematic behavior of a component follows from the accelerometer signals. From measured strains it can be inferred to the local stresses on the surface. However, the crack tip load is not directly accessible as stresses or strains cannot be measured at the notch or crack tip. Information from strain gauges near notches on the surface does not suffice to determine experimentally a crack tip load. Therefore, at first numerical simulations of the tests without cracks are necessary to reproduce the stress states as realistically as possible. In the second step the crack tip load can be determined by formula from fracture mechanical handbooks if an equivalent crack model can be found. Alternatively, the crack tip load can be calculated directly in a simulation with modeled crack.

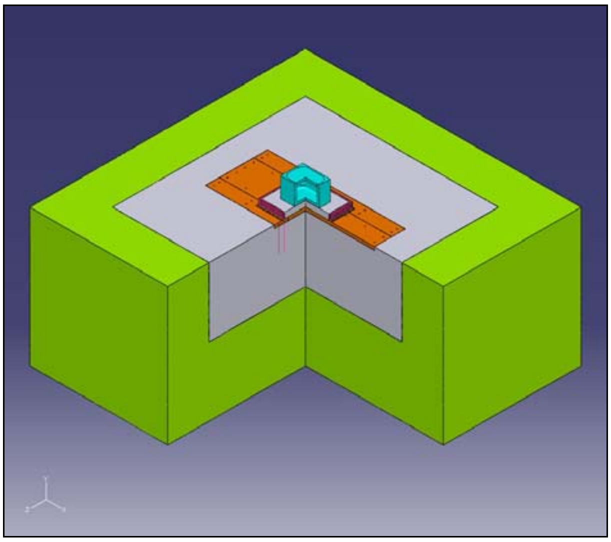

Figure 8. DCI container GC FORM III-2007 with target construction

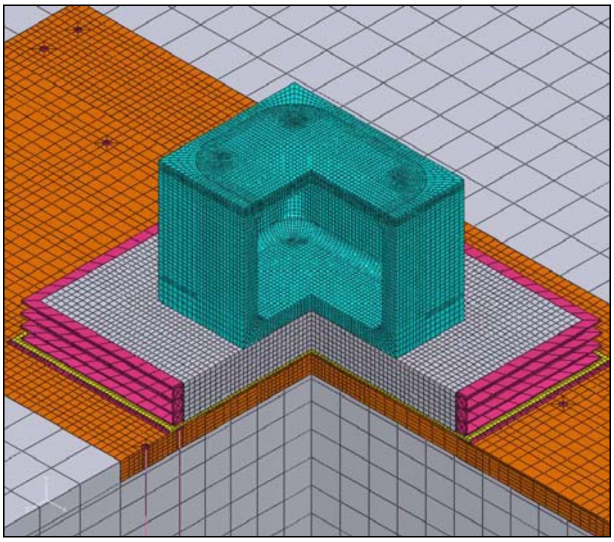

Figure 9. Finite element model acc. to Fig. 8

Numerical simulations of drop tests also facilitate the investigation of worst case load scenarios. The casks hit the target with a very small but unavoidable impact angle (in practice < 0.4°). The stress level inside the component generally decreases with an increasing impact angle. Even very small impact angles may not be neglected particularly at the flat impact of a cask. Therefore, the influence of an impact angle must be assessed newly at every test.

The drop tests with the cubic container were simulated in effortful fully dynamic finite element (FE) calculations using the commercial code ABAQUS/Explicit™ [12]. The FE model is shown schematically in Fig. 8. The voluminous modeling of the target supports the investigation of stress waves propagating in the ground due to the impact. The experimental set-up was modeled as full model to make it possible to analyze also complicated scenarios without symmetry conditions (Fig. 9). At the beginning the cask is placed close above the concrete slab, i.e. the free fall is not calculated. The drop height is taken into account by the initial velocity. The target was modeled in detail including the test stand foundation. Infinite elements surround the ground. Further boundary conditions are not necessary. Contact conditions between parts of the model were defined with ABAQUS option "General Contact" without friction. The container was modeled with all important geometrical properties including the bottom ledge. Dynamic stress-strain curves of the special cast iron GJS/R were provided by project FORM and transferred to an elastic-viscoplastic material model. Concrete slab and mortar layer were described by the Drucker-Prager material model. The underlying IAEA target with cover steel plate behaves elastically. Moreover the evolved ground is modeled elastically.

Figure 10 shows the measured and calculated surface strain in the middle of a side wall of the cubic container. The periodic time of the oscillation is represented by the simulation sufficiently exactly. Altogether the calculation overestimates the measured strain somewhat. For an overview of the impact scenario and the following free vibration of the cask, however, it does not suffice to evaluate some individual signals. For this the calculation results have to be assessed at different positions of the container, especially at the positions with the highest stresses in the structure.

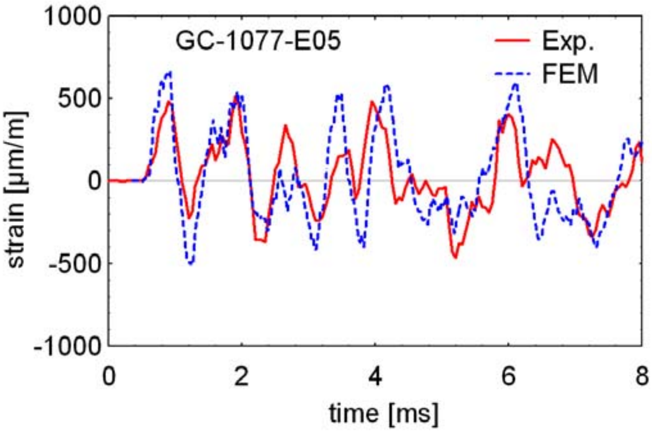

Figure 10. Surface strain in the middle of a side wall of the cubic container during bottom drop from 5.55 m height

CONCLUSIONS

The investigations at cylindrical cast iron casks have shown that the maximum circumferential strain and maximum first principal stress for the horizontal drop are located near the lid engagement independently on the gap width between lid and cask body. An artificial material defect of defined size at this position did not show any crack initiation.

A real target with clearly defined and reproducible properties is essential at drop tests with casks for final disposal. A failure of the concrete target during the test leads to an inadmissible reduction of the stresses inside the cask structure. Due to many design options it is necessary to specify the whole target construction in detail. Particularly the requirements on the compressive strength of the concrete must be met. The improved target construction is proposed as a reference target for drop tests with casks whose mass and base area are covered by the container types VI or VII respectively according to the KONRAD repository acceptance criteria. The suitability of the target construction has to be checked if mass, geometry or drop height of the cask is changed.

Fracture mechanical assessment methods for cast iron with higher contents of metallic recycling material were developed in the project EBER. The variation of the chemical composition and manufacturing process opens a wealth of materials of GJS/R type. These new materials have to be exactly specified by the manufacturer with regard to microstructure and mechanical properties. Only a part will be suitable as cask material. Therefore, the demonstration of safety against failure by fracture with a special casting must be seen related to the individual case. For the practical application it is necessary to transfer the material quality demonstrated at a test cask to other cask geometries and possible serial casks by quality assurance measures.

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