Development of Assessment Methods for Transport and Storage Containers with Higher Content of Metallic Recycling Material

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Abstract

The mechanical behaviour of transport and storage containers made of ductile cast iron melted with higher content of metallic recycling material from decommissioning and dismantling of nuclear installations is investigated. With drop tests of cubic container-like models, the influence of different real targets on the stresses in the cask body and the fracture behaviour is examined. A test stand foundation is suggested, which can be manufactured simply and improves the reproducibility of the test results strongly. The test objects are partially equipped with artificial crack-like defects. Dynamic fracture mechanics analyses of these defects were performed by means of finite element calculations to uncover safety margins. Numerous test results show depending on the requirements that containers for final disposal can be built by means of a ductile cast iron with fracture toughness more than half under the lower bound value for the licensed material qualities yet. The application limits of the material are determined also by the opportunities of the safety assessment methods. This project supports the application of brittle fracture safe transport and storage packages for radioactive materials as recommended in App. VI of the Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (IAEA No. TS-G-1.1).

1 Introduction

Radioactive scrap metal from decommissioning and dismantling of nuclear installations can be recycled at the production of ductile cast iron casks for final storage by special melting processes. An increase of the scrap metal additions leads on the one hand to a favourable reduction of the mass of material for final storage, but on the other hand to a disadvantageous influence on the safety relevant material properties, especially the fracture toughness. The qualification of the new material “ductile cast iron with higher content of metallic recycling material (DCI/R)” for safety relevant applications is a necessary prerequisite for its use as cask material. Suitable safety assessment methods for DCI/R casks were developed up to a certain stage in the already completed projects EBER [1] and EBER II [2]. From the results of static and dynamic fracture mechanics analyses, safety assessment diagrams simply to be handled for crack-like material defects in cask structures were developed. In 2001 the possible use of the new material was demonstrated with a drop test of a container with suitable constructive optimizations (e.g. large fillets), but without impact limiters. It is remarkable, that under the highly dynamic loading conditions during this test, the DCI/R had a fracture toughness value more than half under the lower bound value for the licensed material qualities yet.

After a summarizing representation of these results, we will report about the final investigations and already existing intermediate results in the present research project EBER III. In support of the previous results and for the guarantee of the practical applicability, the developed fracture mechanics assessment methods shall be formulated independent of the location of a future final storage facility considering the situation in Germany. In a series of drop tests with comparatively small but still heavy cast components, the influence of different targets on the component stress and the failure behaviour is examined experimentally and with the help of numerical simulations. Finally, available safety margins shall be uncovered and assessed by a more exact consideration of the geometry of material defects as semi-elliptical surface cracks in components under static and dynamic loads. Therefore, the aim of the project is the definite ascertainment of the application limits of the material for the safety assessment concept.

At the same time, the projects for the maximized use of recycled scrap metal FORM [3] and FORM II [4] were carried out by the German foundry Siempelkamp Gießerei GmbH & Co. KG in Krefeld, which are continued in the research project FORM III [5] now. Problems of the production of the material, constructive optimizations and the quality assurance are topics of these projects. This company produces the test objects and makes the material data available. These data include static as well as dynamic deformation parameters and fracture toughness values in dependence of the temperature, which are needed for the safety assessment procedure.

2 Known Issues

At the preparation and at the work of the projects EBER and EBER II it has turned out that the current knowledge in the following fields of interest is inadequate. Primarily, improvements of the safety assessment concept for casks with higher content of metallic recycling material are necessary. There are published results about the analysis of the mechanical loads of DCI/R casks under accident conditions only as a result of the projects EBER, EBER II and EBER III at present [6, 7, 8, 9, 10, 11]. For casks from the usual ductile cast iron, there are numerous test results from the experience of BAM [12, 13, 14]. They can be consulted, however, only conditionally for statements concerning the safety of cast iron casks with higher content of metallic recycling material, since there are differences in the ductility of the materials and particularly in their fracture mechanics properties [1].

For the use of ductile cast iron there are assessment concepts (e.g. the BAM safety assessment concept [15] or the IAEA recommendations for the prevention of failure by brittle fracture [16]) whose application in detail must be carried out on the basis of well-founded assumptions. On the basis of the finite element method, a procedure for the stress analysis of cubic ductile cast iron containers under mechanical accident conditions (Waste Container Class II) was developed and verified with experimental results in the project EBER [1]. The analysis of the highly dynamic stresses was very successful in this way. By means of the calculated maximum stress and the dynamic fracture toughness values from the project FORM, a fracture mechanics assessment was carried out with a simplified model which allowed statements about the size of permitted material defects only in plane container walls. Under normal operation conditions (Waste Container Class I), we found sizes for material defects which just could be prevented with usual effort for production and non-destructive examination.

Fig. 1. 1 m drop test with the hollow section A1

In the project EBER II [2] this assessment method was extended to material defects in fillets of cubic casks. For material defects in plane container walls new calculation formulae were developed. They are applicable in a bigger parameter range unlike the formulae used in the project EBER, particularly for deeper crack-like flaws. These formulae, originally derived for static load cases, could successfully be used for naturally dynamic drop tests with typical durations of the load of some milliseconds. The equations for the crack tip parameter in the static load case were combined with the stress history from dynamic calculations of the component without a crack. The developed assessment method therefore represents an important progress to common fracture mechanics assessment concepts which often count on the static analysis of flaws in plates [17]. A more exact safety analysis particularly for accident conditions requires the assessment of crack-like flaws with a semi-elliptical shape on the basis of three-dimensional dynamic fracture mechanics considerations. This idea opens up the possibility of allowing larger flaws at the same safety level.

Experimental investigations of artificially built-in crack-like flaws in casks made of ductile cast iron show under accident conditions on the one hand a small crack growth, but on the other hand the safety of these cask structures also in such extreme load scenarios [14, 18]. The prototype cask "cast iron container FORM II" made of a cast iron with higher content of metallic recycling material has not failed at the drop test in the project EBER II. With a single drop test it can only be decided, whether the cask has failed or not failed in the exactly predefined load scenario. A statement concerning the safety margins is not possible in this way. These safety margins shall be uncovered by a series of drop tests. They can be carried out for reasons of cost also at container-like test objects simplified on the essential.

3 Real Targets

A main emphasis of the project is the development of a reference target for the drop tests according to the conditions for final disposal of radioactive waste for the KONRAD repository [19, 20]. Unfortunately, the specification of only the concrete quality in the regulations is not adequate for the creation of reproducible deformation properties of the target. These mechanical properties are, however, of decisive importance for the stresses in the cask structure. The foundation for a drop test in the field of interim storage or final disposal is a real target in contrast to the so-called unyielding IAEA target [16]. The manufacturing of such a target by casting of a concrete foundation in the context of the project EBER II was both expensive and time consuming. At a drop test the foundation is generally destroyed and is usable only once therefore. That is exactly why a layered test stand foundation shall be specified which can be manufactured more simply and is suitable for the execution of the series of tests. As the topmost layer a concrete slab of the quality specified in [19, 20] is used as the primary target. The connection of this primary target to the foundation is of great importance since in the whole the target shall appear as a half-space according to the conditions in a repository. So the influence of the size of the primary target on the stresses in the test object must be negligible.

The test objects are produced in the context of the project FORM III by the above mentioned German foundry. These are altogether 13 hollow sections with the dimensions 1100 x 1100 x 820 mm^3, a wall thickness of 160 mm and a mass of approximately 3.8 Mg, Fig. 1. The wall thickness is the same as in the case of the cast iron container FORM II. This leads to similar cooling conditions during the production process what is of importance for the transferability of the test results to casks. The hollow sections are produced in three series. The first series (FORM III – Series A) covers 4 profiles of the so-called material Ring 1 of the project FORM II. With these test objects 26 drop tests were carried out till now. The radius of the fillets of the hollow sections is 125 mm according to the precomputations. So a plastic deformation can be excluded largely and the hollow sections can be used repeatedly for drop tests. The hollow sections do not show any externally visible damages and no plastic deformations were found, e.g. at the outer corners, till now as predicted.

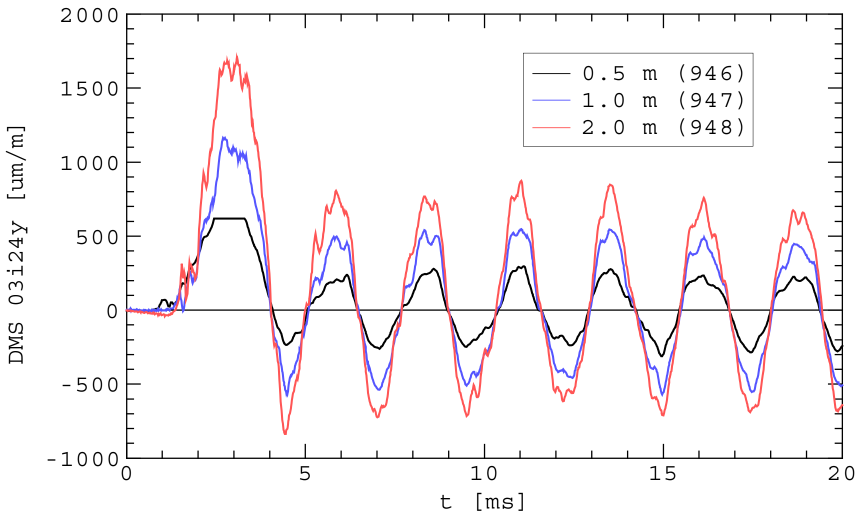


Fig. 2. Strains in the centre of the inner side of the bottom

For the evaluation of the tests the hollow sections were equipped with strain gauges in the centre of all walls inside and outside. Accelerometers were attached on the top side of the test object and also in the corners of the concrete slab. At some tests a laser vibrometer was used for the measuring of the motion of the concrete slab in addition.

The experimental investigations started with some pretests for the specification of the parameters for the drop tests to be carried out later in series. The drop height of 0.5 m was increased first to 1.0 m and then to 2.0 m. Fig. 2 shows the measured strains in the centre of the inner side of the bottom of the hollow section. After the impact with the respective maximum values at the beginning, the bottom oscillates freely with a time period which is independent of the drop height. One recognizes a measurement range overflow at the drop height of 0.5 m after 3 ms. From these results the drop height for the further tests of the series was fixed with a value of 0.8 m. The drop height of 5 m, required for a test according to the Waste Container Class II, is reached at later tests and is without importance for the moment.

The series A of the hollow sections is used for experimental investigations concerning the test stand foundation. The drop tests were carried out as flat impacts of the bottom side of the hollow sections onto the primary target under exactly defined conditions. Only the connection of the concrete slab to the foundation was varied in the first step. The connection was made by a 30 mm thick, wet and compressed sand layer with two different degrees of condensation, by mortar and by synthetic resin as well as loosely only for comparison reasons. At every test a new concrete slab was used.

The test results show, that the highest stresses can be found at the impact side, i.e. the bottom. The connections with mortar or synthetic resin were fundamentally harder than for sand. In the centre of the inner side of the bottom maximum stresses up to 170 MPa were measured. Local decelerations up to 2000 g (g is the acceleration due to gravity) were found after processing with a low-pass filter with a threshold frequency of 10 kHz. These maximum deceleration values were twice as high as in the case of a condensed sand.

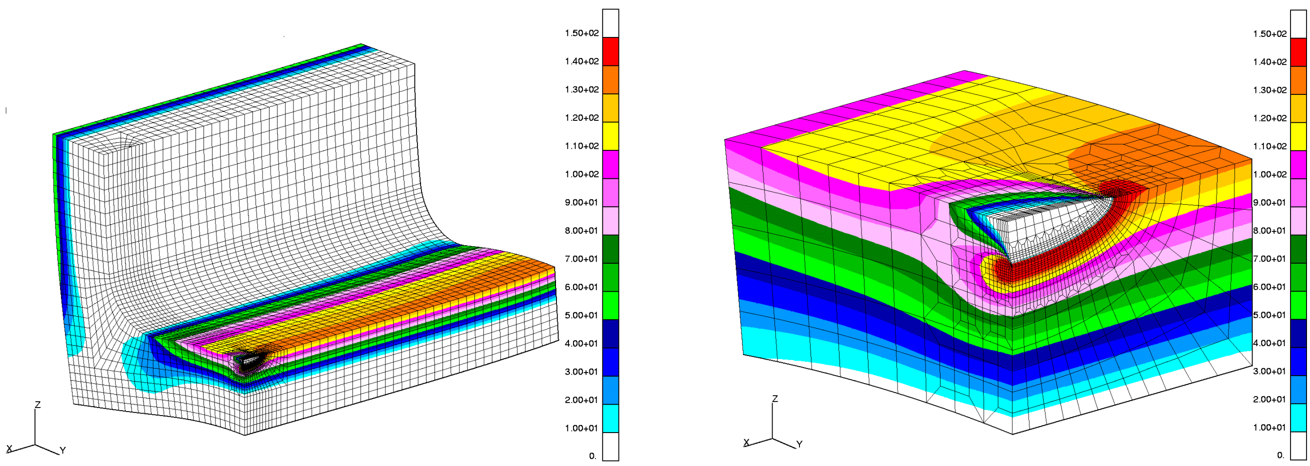
Besides the connection, the material properties of the concrete slab are of significance for the results of the experiments. For the determination of their influence different concrete qualities were defined by variation of the material parameters and examined in detail. The concrete slab with the dimensions of 1.58 x 1.30 x 0.18 m^3 was clamped in a steel frame in any case. Since the concrete is used at our tests only on pressure, an armouring was renounced. The damages found after the tests are mainly small plastic deformations at the surface. A failure of a concrete slab by fracture was watched only at the repetition of a drop test with the same concrete slab.

At earlier drop tests it has turned out that the specifications in the regulations [19, 20] do not suffice for a definition of a target for high reproducibility of the results on repeated execution of a test. The surface properties are not reproducible adequately exactly. In addition, there are free parameters in the practical realization of the requirements. According to the regulations the target is a concrete target with a minimum compressive strength of 35 MPa. At the test the concrete must not fail by fracture which would lead to a reduction of the load otherwise. Any moving of the foundation because of the load must be prevented. In addition, the influence of the soil under the foundation must be negligible concerning the test results.

From the experiments a reference target which fulfils these properties was defined. It was already tested successfully in numerous drop tests. The reference target consists of a concrete slab with German grade B35 which is clamped in a steel frame. The concrete slab gets firmly connected to the foundation by a fast hardening mortar. The manufacturer of the concrete slab must fulfil additional requirements for the quality assurance. A detailed certificate about the characteristics of the concrete is included.

4 Components with Artificial Material Defects

Additional hollow sections are manufactured at present as a part of the project FORM III. The limit of the load of the material and the safety margins shall be examined by the series B and C of drop tests with artificially notched hollow sections. The notches have a depth up to 16 mm (1/10 wall thickness) and a radius of 0.1 mm. They will be built into the bottom, the walls and the fillets and shall simulate material defects in exactly defined way to determine the application limits of the material. The dimensions were chosen consciously conservatively. These hollow sections



a) Full finite element model

b) Model around the crack in detail

Fig. 3. Finite element model of a 1/8 hollow section under static load (scale factor: 50)

are partly produced from new special melts which are selected according to fracture mechanics considerations at the moment. For these new materials the manufacturer makes available static and dynamic flow curves as well as static and dynamic fracture toughness values dependent on the temperature for the calculations on the part of BAM. So the series B and C are primarily different in the fracture toughness. The series C features in addition geometrical optimizations for the reduction of the stress in the structure.

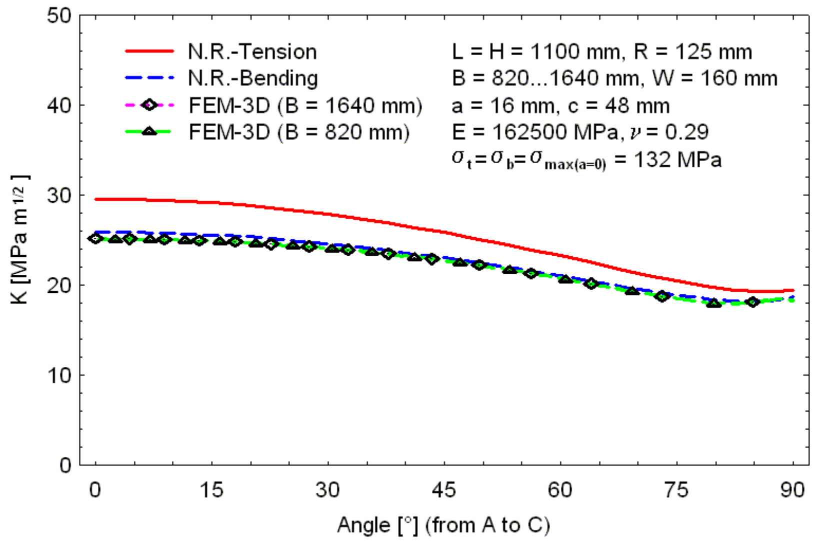


Fig. 4. Stress intensity factor of a crack in the centre of the bottom

The investigations are carried out in 4 steps, in each step with one test object from both series B and C. The drop height is increased from step to step until the failure of the component. After the tests specimens are cut from the hollow sections which contain the artificial flaws. Metallographic specimens containing the flaw are investigated to detect possible crack initiations. These results have influence on the evaluation of the drop tests and the specification of the next higher drop height by BAM.

The experimental investigations are accompanied by computational analyses to the behaviour of the crack-like flaws. Fig. 3 shows the finite element model of a 1/8 hollow section with a sharp semi-elliptical surface crack in the centre of the bottom under static loading conditions. The material behaviour is linear elastic. The stress intensity factor decreases along the crack front from the deepest position to the surface, Fig. 4. At the chosen dimensions the crack of depth *a* and length *c* is a local effect as you can see from the almost identical calculation results for different widths *B* of the hollow sections. A comparison with the well-known static solution by Newman and Raju under pure bending (N.R.-Bending) shows the good precision of the calculation results. It also illustrates that with the solution for pure tension (N.R.-Tension) a conservative estimate of the stress intensity factor for pure bending is possible.

5 Safety Assessment Concept

A fracture mechanics assessment concept was developed for crack-like material defects in the centre of plane container walls and in fillets in the project EBER II [2]. The geometrical shape of these flaws was described by a only two-dimensional model (crack of finite depth, but infinite length) in a conservative way. The effects from the three-dimensional structure of postulated semi-elliptical surface flaws were merely estimated, but not verified there. Therefore, three-dimensional fracture mechanics calculations were carried out in this project to validate the fracture mechanics safety concept. Fig. 5 shows a part from a finite element model with a crack in the fillet region. The safety margins of an assessment on the basis of three-dimensional considerations compared with two-dimensional models could be shown in a series of numerical simulations with semi-elliptical surface cracks with equal crack depth, but different aspect ratios *a*/2*c* from 1/12 to 1/3, Fig. 6. As expected the curve approaches with an aspect ratio getting smaller more and more the solution for an infinitely long crack. The more the crack gets semi-circular, the more the critical range with the high-

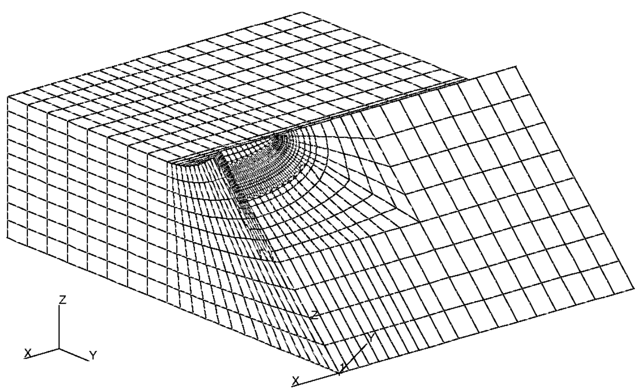


Fig. 5. Finite element model of a crack in a fillet

est stress intensity factor shifts from the deepest position to the surface. This is a known effect which one also finds at cracks in plates. The values for the largest angle of 90° directly at the surface can be considered inexact due to numerical inaccuracies.

It is an important aim of this project to formulate the assessment concept, using the results of the experimental and numerical analysis of drop tests onto various targets, independently of the location of a future final storage facility. The assessment concept therefore does not presuppose any special foundations in a repository, but defines general material parameters as input quantities. These material parameters have to be determined for the location by geotechnical analyses of the foundation. Finally, with the help of the material properties, the size and shape of permissible material defects and the non-destructive examination it will be pointed out, up to which loading limit DCI/R casks would be safe under mechanical accident conditions.

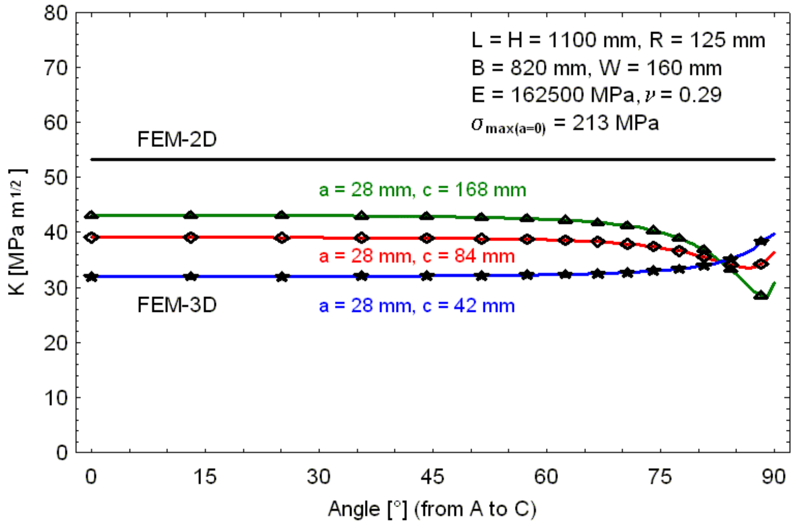


Fig. 6. Stress intensity factor along the crack front in dependence of the crack depth and length

6 Verification of the Safety Concept

The safety assessment concept will be verified with drop tests from 5 m height onto a yielding, but hard target at a temperature of -20 °C according to the conditions for final disposal of radioactive waste for the KONRAD repository. For that the drop test with the cubic cast iron container FORM II will be repeated with larger flaws. Additionally, a geometrically optimized cylindrical prototype cask from a special melt will be produced in the context of the project FORM III, which will be equipped with artificial flaws and also tested by BAM. The experimental results shall give information about the load in selected parts of the casks and can be compared directly with the calculation results from the stress analysis. These verifications are scheduled according to the present planning next year.

7 Summary

The results of the project have shown that DCI/R can be assessed with the developed methods in principle. An important progress was reached in the stress analysis of container-like test objects under impact conditions as well as in the fracture mechanics safety assessment of crack-like material defects. The results can be transferred to the analysis of the highly dynamic load of cast iron casks without impact limiters at drop tests onto real targets. Numerous test results show depending on the requirements that containers for final disposal can be built by means of a ductile cast iron with fracture toughness more than half under the lower bound value for the licensed material qualities yet. The application limits of the material are determined also by the opportunities of the safety assessment methods.

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