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APPLICATION LIMITS OF LOW-DUCTILE CAST IRON FOR RADIOACTIVE WASTE CONTAINERS

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ABSTRACT

Cost-optimized containers for radioactive waste are needed especially for final disposal of non-heat generating low active waste. In Germany such containers should be made of low-ductile cast iron with increased contents of metallic recycling material from decommissioned and dismantled nuclear installations. Nevertheless, they have to fulfil IAEA regulations, repository acceptance criteria and interim storage requirements. Due to the reduced fracture toughness of this material, the influence of postulated crack-like material defects must be carefully assessed. Hence, the application limits of this new material must be investigated, and a series of drop tests with cubic container-like models (mass approx. 4 Mg) onto real targets was performed. The test objects were partially equipped with artificial crack-like defects. These tests examined the influence of different concrete targets on stresses in the cask body and fracture behaviour. Extra-regulatory tests were done until failure of the components. The drop tests were simulated with dynamic three-dimensional finite element calculations. Crack-like defects inside the structure were assessed under quasi-static load as well as dynamic impact conditions. Maximum drop height depended on material quality (expressed by the dynamic fracture toughness), stress-limiting constructive measures, real target strength, and crack size and shape. Limitations of the new cast iron material quality for safety relevant applications were found on the basis of these results. The numerous tests showed that, depending on the requirements, containers for final disposal can be built of low-ductile iron with fracture toughness less than half lower limit for material quality licensed at the moment. Material application limits are thereby also determined through the opportunities granted by safety assessment methods. This project justifies the application of brittle fracture proof 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).

INTRODUCTION

Large amounts of contaminated metal waste arise when decommissioning and dismantling nuclear installations. If it were possible to reutilize part of it as normal non-radioactive material, the volume needed in final storage facilities and, as a result, also costs could be reduced. One idea in this field is to use the scrap metal directly during the production of cast iron containers for final disposal of radioactive waste. The necessary technology for such a manufacturing process already exists [1], and it is possible to create various new grades of nodular cast iron apparently suitable as container material. However, scrap metal recycling during production of nodular cast iron has effects on safety-relevant properties of the material. The material's ability to deform plastically and its resistance to crack initiation and propagation are less compared with the ductile iron normally used for cask manufacture. In particular, a large degree of scrap high-grade steel has a very adverse effect. Therefore, the effort to qualify this new material for safety-relevant applications is increasing.

Figure 1. Drop test with the hollow section B2 from a height of 3.2 m onto the reference target

In the EBER research project "Development of assessment methods for transport and storage containers made of ductile iron with increased contents of metallic recycling material" the Federal Institute for Materials Research and Testing (BAM) is examining which safety margins for such low-ductile iron (called GJS/R) exist, and whether these suffice to manufacture containers according to IAEA regulations, German repository acceptance criteria and interim storage requirements [2]. Numerous drop tests with original size cylindrical casks and cubic containers as well as components of different ductile iron grades have been carried out. The undertaking of such tests was already optimized in earlier research by analysing the influence of different targets, and knowledge in this field was summarized in the definition of a reference target for drop tests onto real targets. In this way, well reproducible experimental results can also be achieved under large-scale test conditions. In particular, exact determination of container stresses in a drop onto a hard rock foundation in final repository can help clarify safety margins with high accuracy.

Numerical simulations of drop tests are carried out as part of stress analysis to find the cask body stresses and strains and their rates, respectively. It turns out that the positions with high stresses are very sensitive to impact conditions. This applies particularly to cubic containers. In addition, constructive details – for instance, the gap between lid and body of cylindrical casks at horizontal impact, or a bottom ledge of cubic containers at flat impact – can change the position of highest stress in the cask wall. Moreover, methods for the fracture mechanics assessment of material defects in casks have been developed.

Previous experimental and numerical research on components made of cast iron with increased contents of metallic recycling material put the main emphasis on a stress analysis of components without any material defects [2, 3]. Continuing these studies, GJS/R fracture behaviour is examined now by drop tests with container-like components artificially pre-cracked with notches

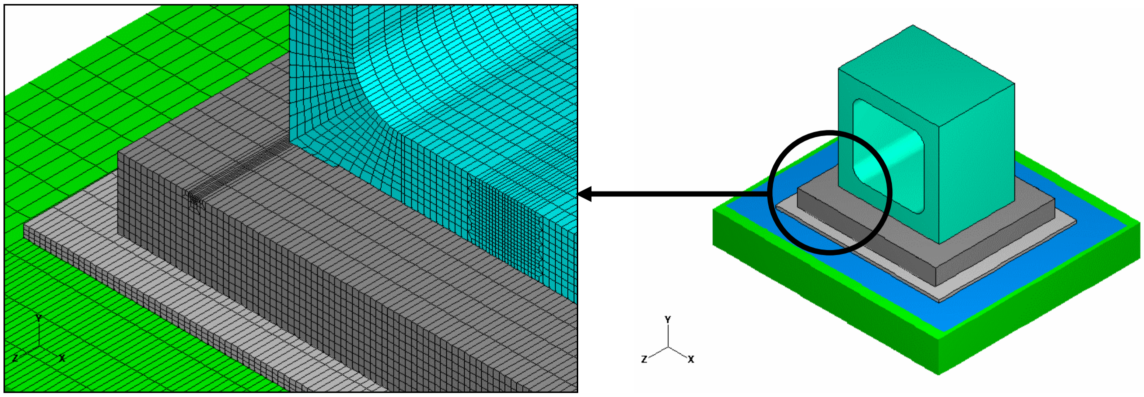

Figure 2. Finite element model with detail for drop tests with hollow sections

of a tip radius smaller than 0.1 mm (Fig. 1). Experimental results with heavy cast iron components in the form of a hollow section should show the limits that can be applied to a material with pre-existing defects. Such material defects always exist from manufacturing. Small defects remain undiscovered during non-destructive testing due to the limits of the ultrasonic test method, and experimental results also give advice on the safety margins of the material. A drop test with an artificially pre-cracked original size prototype cask was carried out. The cask was made of a special low-ductile iron grade with increased contents of metallic recycling material, and the test conditions were taken from the German repository acceptance criteria of the former iron ore mine Konrad [4, 5]. The depth of the machined notches reached up to 1/10 of the wall thickness, i.e. 16 mm. The cracks discovered show the necessity of (1) exact determination of stress level for the fracture mechanics assessment, (2) non-destructive testing with appropriate procedures and size limits for the material being investigated, and (3) probably higher fracture toughness than that of the investigated low-ductile cast iron grades. Otherwise, further constructive measures – for example impact limiters – are necessary to reduce the stress level.

COMPONENT TESTS

Only a few drop tests can be carried out with prototype casks due to the effort involved and cost reasons. Therefore, fundamental correlations are examined better in a series of component tests with container-like models under exactly defined and well reproducible boundary conditions so that individual test results can be compared. Suitable models must demonstrate behaviour representative of the examined cask type. Hollow sections with a volume of 1100 mm x 1100 mm x 820 mm and wall thickness of 160 mm are suitable for cubic containers. Such models can be manufactured simply and comparatively cheaply in larger quantities, and show the bending vibrations typical of cubic structures. The wall thickness corresponds with that of the original container as the mechanical and technological material properties depend on the manufacturing process and, particularly, cooling conditions of the casting. Twelve hollow sections in total were available. They were manufactured by the German company Siempelkamp Gießerei in the context of the research project FORM (optimization of scrap metal recycling) which was supported by German BMFT under grant 02 S 8011. The special castings used showed dynamic fracture toughness values 22…27 MPa√m in fracture mechanics standard tests [6].

The experimental set-up (Fig. 2) is based on the acceptance criteria for the German Konrad repository [4, 5]. According to this, the test object should drop onto a foundation representative of the final repository, which has to be modelled by a concrete foundation of the former German grade B35. These conditions are fulfilled by the reference foundation suggested by BAM. Drop height varies depending on the stress state to be adjusted in the object. The hollow sections should hit the reference target flatly. Highest stresses are anticipated in the middle of the walls with an ideally flat impact onto the bottom of a cubic hollow section. When there are small impact angles in the range of a few degrees, the position of highest stress can move from the middle of the wall towards the adjacent side walls. This is combined in most cases with a reduction in the stress level.

Notches are machined into 8 of the hollow sections available. These notches simulate conservatively postulated material defects by an artificial crack-like flaw so that fracture mechanics methods can be used for the safety assessment of the component. Long notches of constant depth are defined as the geometrical shape of the flaw (Fig. 3). Defects of such size do not appear in the real material, but this does not play a role here as size and shape of the flaw must always be seen in connection with the load. The advantage of large flaws is that a small drop height can be chosen to adjust the needed critical stress intensity to the flaw position. Therefore, one may not conclude on possible drop heights of real casks directly from the low critical drop heights of examined components! Tests with components are designed to investigate the fracture mechanical load limit of the given low-ductile cast iron grade GJS/R.

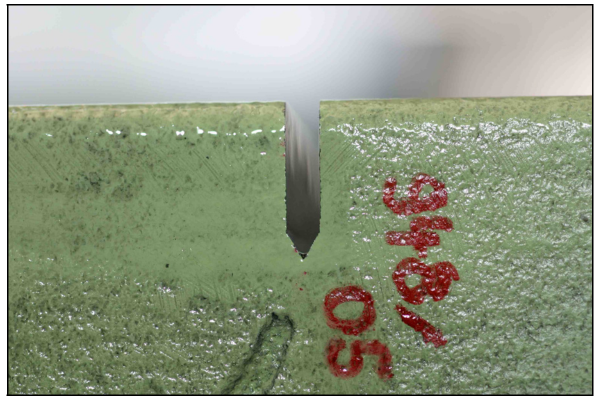

Figure 3. Machined notch at side wall of hollow section

Two series of components were investigated with slightly different geometrical properties: series B from the hollow sections B1, …, B4 with a flat bottom, and series C from the hollow sections C1, …, C4 with a 10 mm thick bottom ledge under the side walls. This bottom ledge represents, for example, a construction optimization to reduce the load on the body. In this way, stress types and values are different in the two types of hollow sections. The notches were machined at different places because they had to be positioned near high stresses in the structure. Series B had notches in the middle of the walls (two outside on the side walls, one inside on the bottom side), and series C had notches inside on the both bottom fillets and, additionally, in the middle of the top side. All the notches were 16 mm deep (1/10 of wall thickness). The machining of the notches required special attention to create a crack-like flaw. An involved mechanical procedure was used to get a notch tip radius of 0.1 mm at an opening angle of 60°. The fillet radius of all the hollow sections was 125 mm so that plastic deformation could be excluded in these areas. The mechanical preparation of the hollow sections was done by Siempelkamp Gießerei.

The hollow sections were equipped with 14 strain gauges in the middle of the walls without notches and 4 accelerometers in the corners on the top side to record the course of the tests in detail. The kinematic behaviour of the component was recorded by the accelerometers, and local stresses came from the strains measured on the surface. The

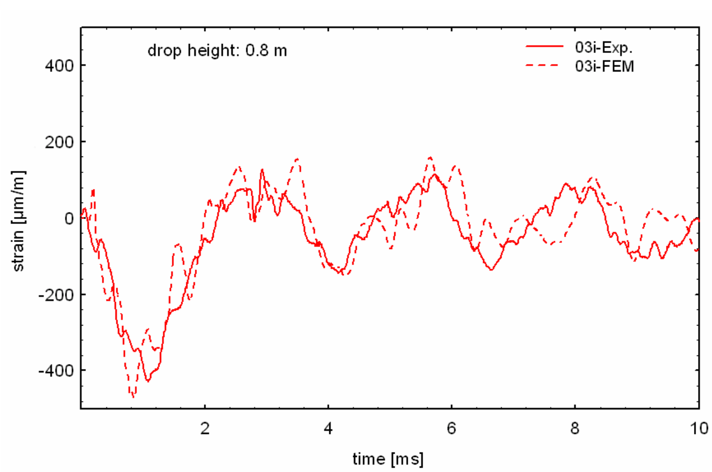

Figure 4. Measured and calculated strains inside in the middle of the bottom of hollow section C1 (drop height: 0.8 m; impact angle: 0.1°)

crack tip load was not directly accessible as stresses or strains cannot be measured at the notch tip. Moreover, information from strain gauges near the notches at the surface does not suffice to determine a crack tip load. Therefore, numerical simulations of the tests with a crack modelled in the hollow section were required to achieve needed accuracy in calculation of the crack tip load (Fig. 4). Test conditions have to be reproduced as realistically as possible. If the investigated material defect is small in comparison with component dimensions, estimation methods can be used without complicated numerical modelling of the crack [7]. The simulation procedures were first tested successfully with the hollow sections without notches.

Several drop heights (0.2 m; 0.8 m; 1.8 m; 3.2 m) were chosen up to the intended failure by fracture. Estimation of the critical drop height was based on the correlation between critical crack depth, crack shape, crack tip load and fracture toughness, which was found for cracks in flat walls and fillets under both static and dynamic loading conditions [8]. The notches were considered conservatively as sharp cracks. Therefore, a critical drop height of about 0.7 m was found for the notches both in a wall of series B and a fillet of series C. Finally, a critical height of 0.8 m was fixed because of the unavoidable small impact angle in practice as opposed to an ideal flat impact. The highest drop height of 3.2 m duplicated the load. One drop test exactly was carried out with every hollow section onto the reference target at a temperature of -40°C. Specimens were taken from near the notch tip after every test to examine possible crack initiation under the microscope as part of the FORM project.

Figure 5. Crack at hollow section C3

The test temperature was lowered conservatively to -40°C. Therefore, material fracture toughness was at the lower end of the brittle-ductile transition range. Hence, linear elastic fracture mechanics methods were still applied to cracks in large hollow sections as well as small test specimens. Application of elastic plastic fracture mechanics with determination of the J integral would be required for materials with higher ductility. However, the drop test with a prototype cask was carried out according to the regulations for final disposal at a temperature of -20°C [4, 5].

CONTAINER STRESSES

Fracture failure can be caused by unavoidable material defects from manufacturing which were not discovered in non-destructive testing. Therefore, the question must be asked of what material defect sizes should be permitted for safety-relevant applications. According to the usual fracture mechanical assessment concepts [9, 10], crack initiation is not permitted; i.e. the fracture mechanical load must always be smaller than the material resistance to crack initiation – in our case, the dynamic fracture toughness. Since the hollow sections always hit the foundation in the drop test with a small angle (in practice $< 0.4°$), the individual notches are loaded differently. In general, the stress level in the component decreases with a larger impact angle. Therefore, the fracture mechanical load – in this case, the dynamic stress intensity factor – must be calculated directly in long dynamic fracture mechanical calculations for each notch modelled as sharp crack in the individual complicated load scenario.

Fully dynamic numerical calculations were executed with the commercial finite element code ABAQUS/Explicit. The experimental set-up was described as full model (as opposed to half or quarter model) to also enable a complicated load scenario analysis without assuming the symmetry of the problem: Fig 2. At the beginning the hollow section was placed over the concrete slab; i.e. the free fall was not calculated. Drop height was taken into account by the initial velocity, and the complete layered foundation was modelled on top of the IAEA test stand target. Infinite elements formed the boundary of the ground beneath. Further boundary conditions were not necessary. Contact conditions were controlled by the ABAQUS option “General Contact” without friction, and the elastic-viscoplastic material model for cast iron used measured rate-dependent flow curves. The concrete slab and a mortar layer connecting with the IAEA target were described by an elastic-plastic material model with hardening. The IAEA target with a steel slab on top behaved elastically, and the surrounding soil was also modelled elastically.

Table 1. Results of post-test research

drop test	drop height	damage of the concrete slab	crack initiation (acc. to microscopic examination at Tech. Univ. Bergakademie Freiberg on behalf of Siempelkamp Gießerei [11])
B4	0.2 m	no	no cracks
C4	0.2 m	no	no cracks
B1	0.8 m	no	microcracks at notch tip and in vicinity of notch
C1	0.8 m	no	no cracks at notches in side walls, microcracks at one of the notches in fillet
B3	1.8 m	no	small cracks at notch tip
C3	1.8 m	no	small cracks at notch in side wall, long crack at the notch in one of the fillets
B2	3.2 m	no	long cracks at all notches in side walls
C2	3.2 m	yes	no cracks at notches in walls, central cracks starting from notches in fillets

Table 1 contains the post-test results on crack initiation with different loads at increasing drop heights. The smallest drop of 0.2 m (half the critical load) led to crack loads below the fracture toughness for crack initiation. No cracks were found as expected. When reaching the dynamic fracture toughness of the material, microcracks appeared at the notch tips and in the vicinity of the notches. The hollow sections were then overloaded intentionally. Small cracks arresting at the notches in the side walls were found after raising the drop height to 1.8 m (about 50% overload), but one long crack starting at a fillet notch went through the component C3 (Fig. 5). At a drop height of 3.2 m (approximately double the critical load), long cracks started at the notches in the side walls of the hollow section B2, which led to total failure. Long central cracks were also found at the fillets which, however, did stop. No crack initiation occurred at the notches in the walls of hollow section C2 due to the target. Unlike in the other tests, the concrete slab was broken. As a result, other loading conditions occurred in the hollow section with generally lower stresses at the notches. Therefore, the hollow section with the flat bottom (series B) failed while the hollow section optimized geometrically with a bottom ledge (series C) destroyed the (non-reinforced) concrete. This shows

Figure 6. Drop test with container GC FORM II from a height of 5.55 m

impressively the advantages of optimized construction. In general, sudden failure of the component must be expected when the critical load is reached.

DROP TEST WITH ORIGINAL SIZE PROTOTYPE CASK

Prototype cask testing was carried out in accordance with the Konrad repository acceptance criteria [4, 5]. The 2000 mm x 1600 mm x 1450 mm cubic cast iron container GC FORM II weighted about 15.8 Mg. Four notches (89 mm long, 6.6 mm deep) were machined in the fillets and one notch (122 mm long, 16 mm deep) in the middle of the inside bottom. The flaws were circular in shape due to the mechanical technique used. A surrounding ledge as geometrical optimization below the side walls reduced container stresses. The container body was manufactured from the special cast iron GJS/R FORM II. Fig. 6 illustrates the bottom drop test from a height of 5.55 m (5 m plus extra height for missing contents) flat onto the reference target at a temperature of -20°C.

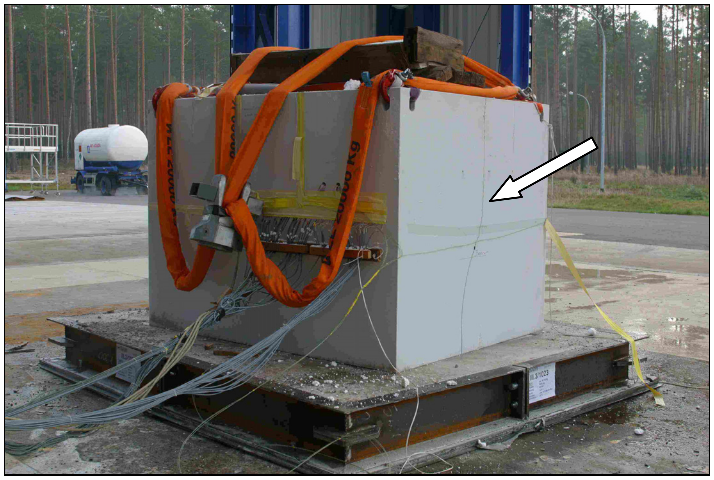

Figure 7. Crack in a side wall of container GC FORM II after the test

Long cracks appeared in the test (Fig. 7), and the overcritical notch in the container bottom caused failure by fracture. The size of this artificial flaw was designed according to current size limits in non-destructive testing for cast iron grades with a fracture toughness twice that of the material here. In addition, an improved test procedure was the test object hitting the target almost ideally in the flat position. The volume strength required of the concrete was fulfilled up to the surface of the slab. Experimental results show clearly that overcritical flaw sizes cannot be tolerated. Therefore, specifications for ultrasonic non-destructive testing must be adjusted to the cask iron grade used, which will involve more work in non-destructive testing. The fracture toughness of low-ductile cast iron should also be improved.

CONCLUSIONS

The material properties investigated in low-ductile cast iron, cask designs, stresses in cask structures and safety aspects show that the fracture toughness of the material and stress intensity factor of flaws must be harmonized very closely. Further optimizations are also necessary. In respect to material, fracture toughness should be increased if possible. Specifications for non-destructive testing of components must also be adjusted to the material quality used to exclude inadmissible material defects. In respect to safety assessment, further drop tests with original size prototype casks will be carried out in 2007 and 2008 with improved low-ductile cast iron grades.

ACKNOWLEDGMENTS

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