ASSESSMENT OF DYNAMICALLY LOADED SURFACE CRACKS IN CUBIC CONTAINERS

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ABSTRACT

BAM is the German competent authority for design testing of packages for radioactive materials and develops in a research project improved fracture mechanical assessment methods for cracks in the highest stressed regions of cubic containers made of ductile cast iron. For that purpose postulated surface cracks in the centre of the container walls and grooves are investigated numerically. In the static case we found relations between the crack tip parameter (stress intensity factor or the J-integral, respectively), stress load, crack depth, container geometry, and material behaviour. In the dynamic case it could be shown, that the dynamic crack tip parameter can be estimated by empirical formulas with the time-dependent "crack-free stress" inserted. This crack-free stress is calculated dynamically under drop test conditions without a crack, but at the position of interest in the container structure. Such a somewhat surprising result can be explained by the fact, that the drop event happens in the range of milliseconds. That is slowly enough for the crack to behave quasi-statically although the crack is loaded with a dynamic, i. e. time-dependent stress. Based on these calculations the critical crack depth is given as a function of the stress, the material quality (defined by the fracture toughness) and the wall thickness of the container for surface cracks in the centre of walls as well as in grooves of a cubically shaped container.

INTRODUCTION

The assessment of a fracture safe ductile cast iron (DCI) cask design must ensure the integrity of transport and storage casks for radioactive materials under the most damaging accident conditions. Based upon the determination of the mechanical impact behaviour and stress analysis of the cask design, sufficient material properties like fracture toughness must be attained in serial cask production. The first BAM safety assessment concept [1, 2] established in the 1980s required only a reduced fracture mechanical analysis because of stress limitation at a level of approximately 50 % of material's yield strength, and appropriate quality assurance measures which ensure only tolerable crack-like defects within the cask structure considering lower-bound fracture toughness down to -40 °C. However, the need of a better material's utilisation resulting in higher stress levels, the consideration of a highly dynamic cask behaviour for specific applications, and material qualities from higher scrap metal additions in smelting require improvements of that safety assessment concept.

The German approval and licensing procedures for shipping and storage casks for radioactive materials made of ductile cast iron relied in the first approach mainly on prototype testing in order to demonstrate sufficient low stress levels and sufficient material toughness for the most unfavourable accident conditions. Owing to the rapid development of numerical calculation methods, analytical and numerical safety assessment methods, considering fracture mechanics, should be appropriate for an improved safety concept. It will require a complete fracture mechanical analysis based on a combination of material testing (like fracture toughness measurements), calculation of applied stresses, and inspection standards. The assessment of postulated cracks within cask structures has been investigated to qualify the intended approaches and criteria to prevent failure by fracture initiation. These cracks simulate non-detected material defects from non-destructive inspection.

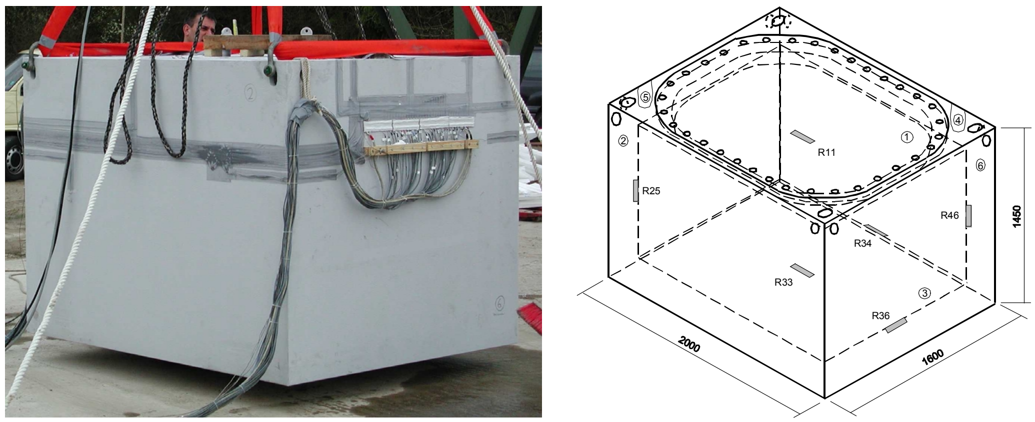


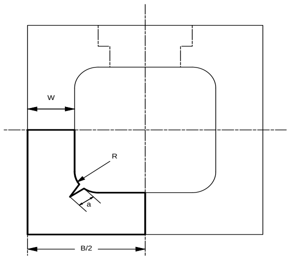
Figure 1, German cubic waste container with artificial crack-like defects

As an example, Fig. 1 shows a German cubic waste container made of ductile cask iron with postulated crack-like material defects in the highest loaded parts of the structure. BAM has developed a method to calculate a pseudo-dynamic crack tip parameter to assess such material defects. The dynamic stress intensity factor of postulated cracks under drop test conditions is estimated using static fracture mechanical formulas. The extent of dynamic effects during a container accident scenario is discussed from the fracture mechanical point of view. Available assessment methods often do not take into consideration dynamic impacts but more or less steady state conditions as a possible approach. Finally, the proposed method is demonstrated for the case of a 5 m drop onto a real target, simulating a handling accident inside a repository.

STATIC FORMULAS FOR CRITICAL CRACK DEPTH

The safety assessment of cracks in grooves or in walls of cubic containers made of ductile cast iron requires the solution of the appropriate fracture mechanical problem. The crack tip parameter (stress intensity factor K_I or the J-integral, resp.) must be calculated numerically or analytically. In some cases the localized crack configuration inside the cast structure may be substituted by a more simple crack problem with a solution already available from literature. A literature survey showed that fracture mechanical solutions from handbooks for cracks in grooves do not exist or are not suitable for the investigated cubic container designs or are of low accuracy. Additionally, elastic-plastic effects in the vicinity of the crack tip should be considered. Therefore, new static fracture mechanical solutions for cracks in grooves and plane container walls were developed. The ductile cast iron is assumed as linear elastic with Young's modulus of E = 162500 MPa, Poisson's ratio of ν = 0.29, and the mass density is 7000 kg/m^3,or elastic-plastic with a flow curve (yield strength $\approx$ 400 MPa) from measurements with ductile cast iron melted with higher content of metallic recycling material [3]. Note, that the following curves are only valid for the material behaviour assumed in this case.

The calculation of the static crack tip parameter of a semi-elliptical surface flaw requires an extensive numerical solution of a dynamic three-dimensional crack problem. As a simplification of this real three-dimensional problem only a part of the container was loaded statically by bending under plane strain conditions (Fig. 2).



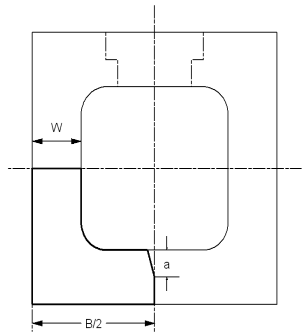


Figure 2,
Schematics of the investigated cracks in grooves (a) and container walls (b)

The crack tip parameter was calculated numerically by means of the finite element code ABAQUS [4] and expressed by a formula of the form

$$K_I = F\,Y_m\sqrt{\pi a} = \sqrt{J\frac{E}{1-\upsilon^2}}$$

with the load parameter F, the geometry function Y_m, and the crack depth a. The results of 192 finite element calculations were fitted to a suggested polynomial equation with the following parameter field as input:

wall thickness W:	160 mm
container width B:	1450, 1680, 2000 mm
radius of grooves R:	0, 1, 5, 10, 20, 30, 40, 50, 75, 100, 125, 150, 175, 200 mm
crack depth a:	0, 2, 4, 8, 16, 32, 64, 128 mm

As an example, Fig. 3 shows the stress intensity factor in a groove for a constant bending stress of 200 MPa in the centre of the container wall.

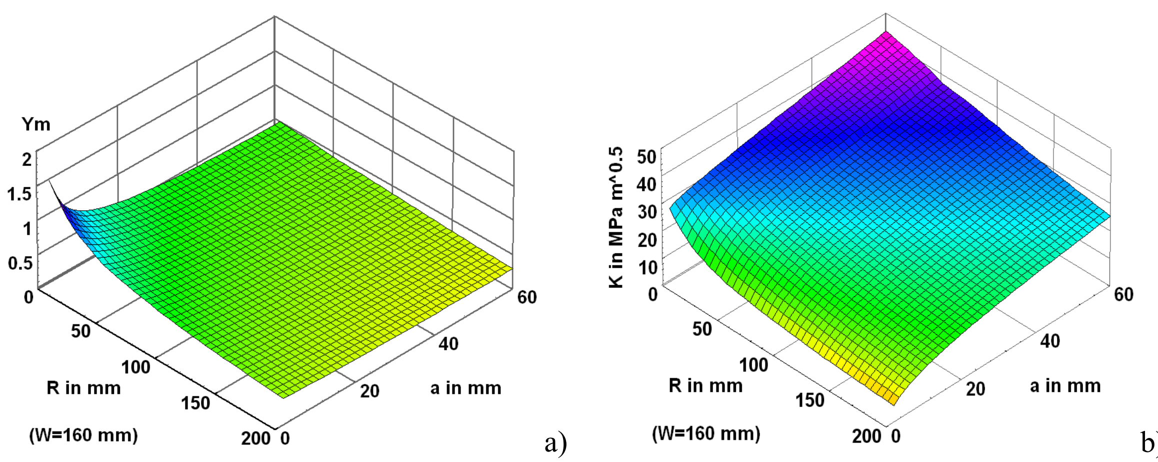


Figure 3, Geometry function (a) and stress intensity factor (b) for a crack in a groove

From the calculation results we derived formulas for the critical size of the crack for the investigated crack problem. Fig. 4 presents the critical size of a crack in a groove with a radius of 125 mm in a cubic container with a wall thickness of 160 mm and an assumed width of 1680 mm. Fig. 5 shows the corresponding results for a crack in the centre of a plane container wall.

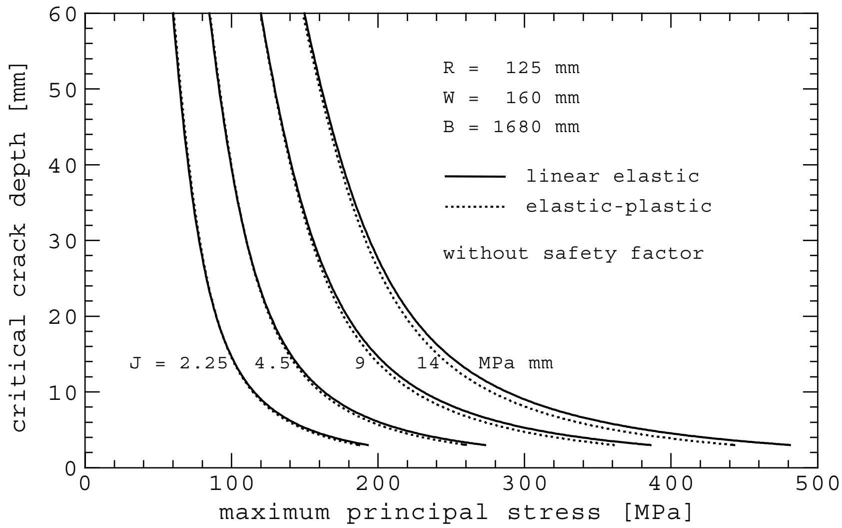


Figure 4, Critical depth of a crack in a groove

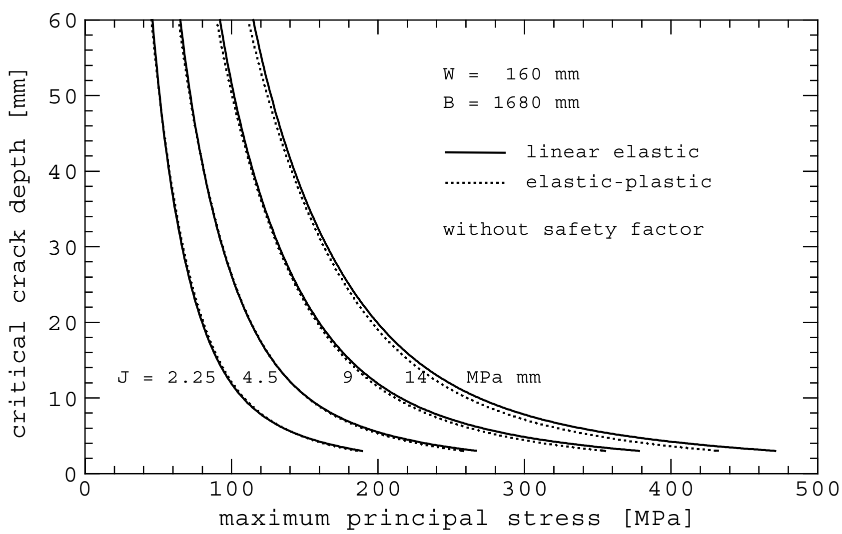


Figure 5, Critical depth of a crack in the centre of a plane container wall

The calculations for both figures do not contain a safety factor, that must be selected according to the field of operation [5]. The critical crack depth is shown as a function of the “crack-free stress”, i. e. the local maximum principal stress from a calculation without a crack, but at the position where the crack would be. The graph with J = 2.25 MPa mm or K_I = 20 MPa m$^{1/2}$ is typical for low quality material with high scrap metal additions. Casks made of such a material are not yet licensed. The application of such a material is planned for waste containers to support decommissioning activities in Germany. The value of J = 14 MPa mm or K_I = 50 MPa m$^{1/2}$ is the lower bound value according to the BAM safety concept from year 1985 [1].

Depending on the cask structure, the real crack configuration may be assessed by the above considered simple two-dimensional crack solutions. Especially, if the effects from additional free body surfaces can not be neglected, then a full three-dimensional treatment of the problem is necessary.

ASSESSMENT OF DYNAMICALLY LOADED CRACKS

The drop test of a container according to the licensing tests is a highly dynamic load scenario. Normally, the investigation of the dynamic behaviour of cracks inside a cask structure under drop test conditions requires an extensive three-dimensional numerical analysis. Nevertheless, it could be shown, that for the investigated crack configurations the dynamic crack tip parameter (K_I, J) may be estimated by our empirical static formulas with the time-dependent "crack-free stress" inserted [6]. This crack-free stress is calculated dynamically under drop test conditions without a crack, but at the position of interest in the container structure. Such a somewhat surprising result can be explained by the fact, that the drop event happens in the range of milliseconds. That is slowly enough for the crack to behave quasi-statically although the crack is loaded with a dynamic, i. e. time-dependent stress. This result is rather important for Type B packages equipped with impact limiters, because in those cases the strain rate is lower than in the case investigated without impact limiters.

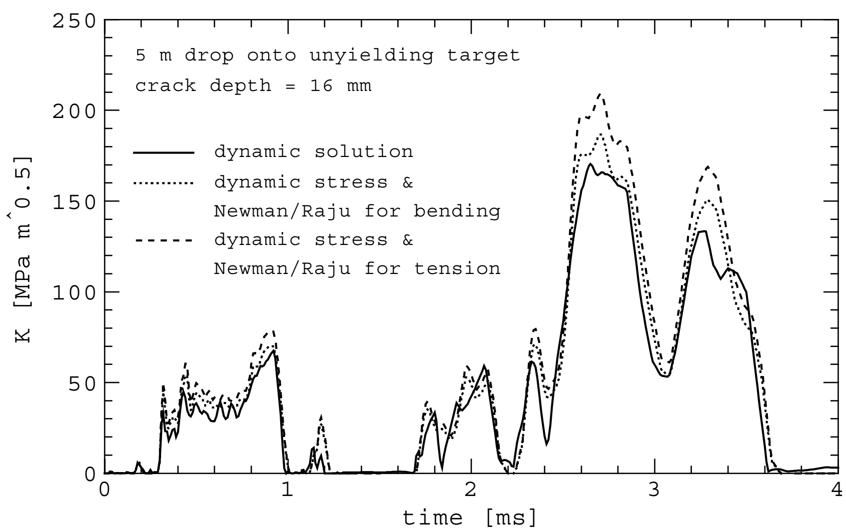


Figure 6, Stress intensity factor for small cracks

The used crack-free stress is the result of a dynamic finite element analysis without a modeled crack. The advantage is, that no dynamic finite element analysis with a modeled crack is required. Small finite elements close to a crack tip result in very small time increments. Thus, less finite elements and less computer time are needed. An explicit time integration scheme is more efficient.

Note, that the method is an approximation, not an exact solution of the crack problem. Therefore, the method must be verified for the selected crack problem with a dynamic three-dimensional numerical solution. It is not applicable e. g. for very short impact events.

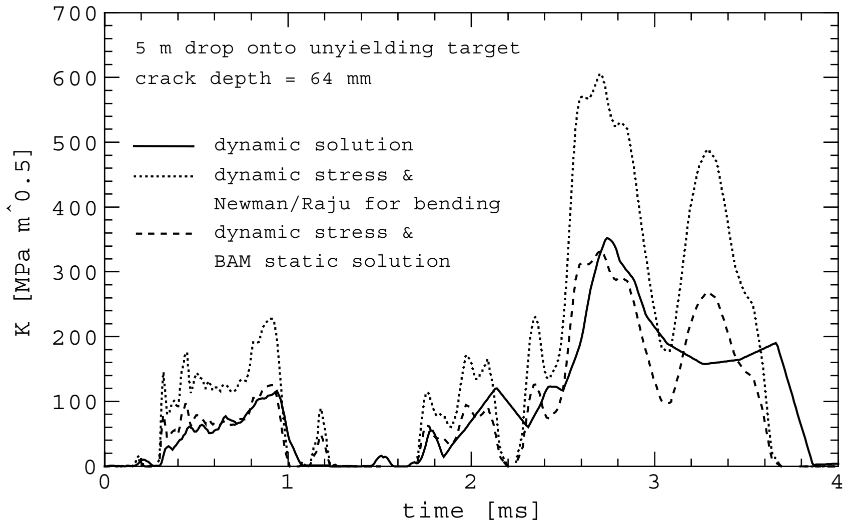


Figure 7, Stress intensity factor for deep cracks

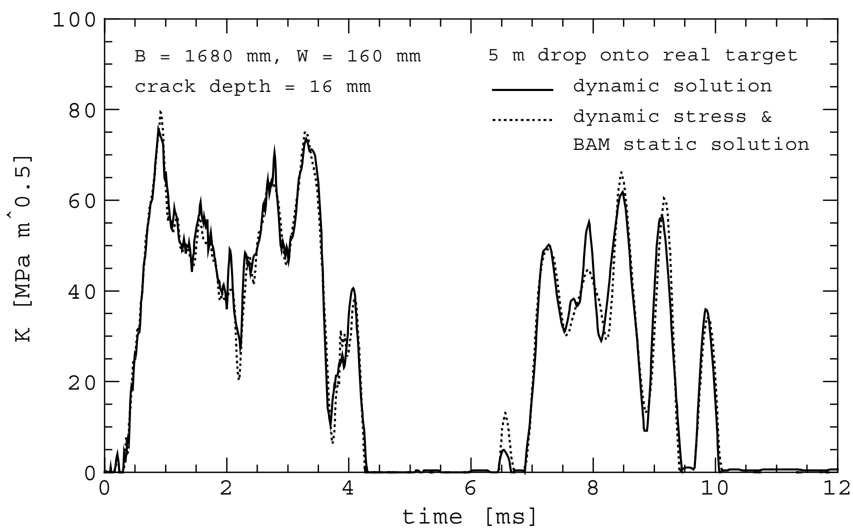


Figure 8, Stress intensity factor in the centre of a container wall

For small crack depths a plane container wall may be considered as a plate. Accurate results for the static stress intensity factor of a surface crack in a plate of finite thickness subjected to tension and bending loads are available from a empirical equation proposed by Newman and Raju [7] who fitted polynomials with the results of static three-dimensional finite element computations. Fig. 6 shows the calculation results for a 5 m drop onto an unyielding target to test the method for the highest possible strain rates. The equation for pure bending is better suited than the equation for pure tension. Both equations approximate the numerically calculated maximum crack tip parameter ("dynamic solution") in a conservative manner. Fig. 7 demonstrates, that for deep cracks the model of a plate is not sufficient to predict the time-dependent behaviour of the stress intensity factor, but the proposed BAM solution reflects better the container structure.

APPLICATION

The behaviour of a postulated crack in a wall of a German cubic waste container design impacted by the drop onto the storage facility foundation from 5 m height, not equipped with impact limiters, according to the preliminary Konrad repository acceptance criteria [8, 9] was investigated. The drop test was simulated numerically without and with cracks of different crack depths. The calculated really dynamic crack tip parameter was compared with the pseudo-dynamic crack tip parameters to find more convenient methods to assess the cracks. The stress intensity factor estimated from the dynamic stress (model without a crack) and the BAM static solution predicts the dynamic solution (model with a crack) from the finite element calculation with sufficient accuracy (Fig. 8).

SUMMARY

The critical crack depth was calculated as a function of the stress, the material quality (defined by the fracture toughness) and the wall thickness of the container for surface cracks in the centre of walls as well as in grooves. The application of static solutions of crack problems to time-dependent load scenarios is possible in special cases, if the rise time of the load stress is "long enough" (typical time scale in milliseconds), i. e. if the crack tip behaviour can be considered quasi-statically in spite of a non-static load. Hence, the prerequisites of the used Newman/Raju solution are not violated in our application. Again, any use of static equations with time-dependent parameters must be tested intensively in each case.

The presented safety assessment method is applicable for crack-like defects in container walls far away from edges and in grooves, and for elastic as well as elastic-plastic material behaviour. It uses an approximation, not an exact solution of the crack problem. Therefore, the method must be verified for the selected crack problem in question. It is e. g. not applicable for very short impact events.

ACKNOWLEDGEMENT

This work is supported by the German Federal Ministry of Education and Research under contract No. 02 S 7788.

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