DYNAMIC FRACTURE MECHANICS ASSESSMENTS FOR CUBIC DUCTILE CAST IRON CONTAINERS

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Abstract — An improved BAM safety assessment concept for the cask material ductile cast iron (DCI) to cover higher stresses in the cask body, highly dynamic load scenarios, and a broader range of material qualities will require more extensive fracture mechanics analyses based on a combination of material testing, calculation of applied stresses, and inspection standards. As an example, the brittle fracture mechanics assessment of a surface crack in a plate due to the dynamic load from the 5 m drop of a cubic container (not equipped with impact limiters) onto a reinforced concrete target is investigated. The numerically calculated time-dependent stress intensity factor is compared with a previous static solution with the same loading history inserted. For the scenario studied the differences between the curves are negligible because a dynamic load of the cask within a time scale of milliseconds can be considered as a quasi static load for the crack.

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 established in the 1980s (1,2) required only a reduced fracture mechanics analysis because of stress limitation at a level of approximately 50% of the 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, a better use of the material properties resulting in higher stress levels, the consideration of highly dynamic cask behaviour for specific applications, and material qualities resulting 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 rely mainly on prototype testing in order to demonstrate sufficient low stress levels and sufficient material toughness for the most unfavourable accident conditions. As a result of 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 mechanics analysis based on a combination of material testing (like fracture toughness measurements), calculation of applied stresses, and inspection standards. The assessment of postulated material flaws within cask structures has been investigated to qualify the intended approaches and criteria to prevent failure by fracture initiation. The stress intensity factor of dynamically loaded simple crack-like material defects was numerically calculated and verified by comparison with analytical solutions of the same crack configuration. Then, the behaviour of a postulated crack in a wall of the German container design Type VI 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 reference was investigated. 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. BAM requires verification of the usefulness of such (quasi-) static equations under dynamic accident conditions.

SAFETY ASSESSMENT CONCEPT FOR DCI CASKS IN GERMANY

The experimental proof of container strength by prototype testing, or by reference to previous tests of a similar nature, combined with the complete approval design assessments ensures integrity and sufficient tightness of a cask design under the most damaging accident conditions. These safety goals are endangered by inadmissible plastic deformations of the components of the containment, particularly those of the sealing system, or by material fracture. Therefore, the safety concept, hitherto used as a practical approach, defines the following requirements.

(1) The maximum tensile stress in the cask structure for the most unfavourable accident conditions may not exceed 50% of the material’s yield stress. This value results from numerous successful drop tests with full size prototype casks in combination with the material definitions below.
(2) Minimum material properties of ductile cast iron in terms of the yield stress ($R_{p0.2} \geq 180$ MPa), tensile strength ($R_m \geq 250$ MPa), elongation at fracture ($A_5 \leq 6\%$), percentage of pearlite ($\approx 20\%$), and type of graphite (no chunky graphite) must be met. If the strain rates during the cask impact are low enough to allow the use of static values of these material properties, and if the stress is limited as above, then the assessment of fracture toughness $K_{lc}$ in a specific design case is not necessary, which has been verified in extensive investigations of ferritic DCI over a broad range of microstructure and temperature. Elsewhere, $K_{lc} \geq 50$ MPa.m$^{1/2}$ at a temperature of $-40^\circ C$ must be shown.

(3) It is necessary to show by means of non-destructive testing methods and procedures for the inspection of the cask structure (such as surface crack inspection methods and ultrasonic testing) that the size of acceptable material defects is well below the critical flaw sizes, e.g. indications with a flaw depth of more than 10% of the wall thickness are inadmissible.

(4) Quality assurance measures must ensure an adequate level of cask properties during series production, depending on the approved cask design, by inspecting important manufacturing parameters, and the specified material properties.

This approach is applicable further on, but if the above conditions are not fulfilled, then a more extended evaluation using fracture mechanics is required.

The method to be used in this case postulates a semi-elliptical reference flaw with an aspect ratio (length to depth) of 6:1 or greater, and flaw depth $a_e = 15$ mm with a wall thickness $w < 150$ mm, and $a_e = w/10$ with $w \geq 150$ mm (Figure 1(a)). The stresses in the unflawed cask structure are calculated according to the mechanical test conditions from the field of operation (defined by the IAEA regulations for the safe transport of radioactive materials, technical acceptance criteria for the German interim storage facilities, or preliminary requirements for the German Konrad repository). If the strain rates in the cask body are greater than $1$ s$^{-1}$, the impact scenario is considered as a dynamic load case. In the next step a crack tip parameter (dynamic stress intensity factor $K_{d,app}$, dynamic contour integral $J_{d,app}$) of the crack-like reference flaw is calculated at the location of the highest applied stress with the highest stress component normal to the plane of the flaw. According to the fundamental fracture mechanics theory, the level of the applied crack tip parameter must be less than the critical value for the material’s fracture toughness in the same form ($K_{d,mat}$, $J_{d,mat}$). The laboratory fracture test to obtain the (dynamic) material parameter must take into account the highest loading rate, lowest temperature, and the effects of sample size(3). Under accident conditions a minimum safety factor of $\sqrt{2}$ in fracture toughness is allowed if the loading parameters and postulated flaw sizes are upper bounds and the fracture toughness is a lower bound from statistical assessments. Alternatively, a drop test at the lowest temperature with a pre-cracked prototype cask in the most critical drop orientation also represents a fracture mechanics safety assessment. In this case the material quality of the prototype cask defines the limitation of the representative material properties for the series cask production(4). These procedures are in compliance with the basic guidelines for fracture safe cask design and appropriate fracture mechanics assessment methods of the draft IAEA Safety Standards Series No. ST-2, Appendix VI(5).

**ASSESSMENT METHODS**

A cask design is safe against brittle fracture if the relationship

$$K_{d,mat} > K_{d,app}$$

holds for the relationship

$$K_{d,mat} > K_{d,app}$$

Figure 1. (a) Semi-elliptical surface flaw. (b) edge crack in a plate.
can be shown at each position in the cask structure and at any time. The applied stress intensity factor $K_{I, \text{appl}}$ must be calculated numerically or analytically. Possibly, the localised crack configuration inside the cask structure may be substituted by a more simple crack problem with a solution already available from the literature. As an example, crack-like flaws in the walls of a cubically shaped container may be considered as semi-elliptical surface cracks in a plate of finite thickness. Static solutions of this fracture mechanics problem are used in the ASME Boiler and Pressure Vessel Code\textsuperscript{6} rules for construction. Accurate results for the static stress intensity factor of such a surface crack subjected to tension ($\sigma_t$) and bending ($\sigma_b$) loads are available from the empirical equation

$$K_I = (\sigma_t + H\sigma_b) \sqrt{\frac{\pi a c}{Q}} F\left(\frac{a c}{w b}, \phi\right)$$

with $0 < \frac{a c}{w b} \leq 1$, $0 \leq \frac{a c}{w b} < 1$, $c/b < 0$, $0.5$ and $0 \leq \varphi \leq \pi$ proposed by Newman and Raju\textsuperscript{7} who fitted polynomials with the results of static three-dimensional finite element computations (for a definition of the dimensions see Figure 1(a), the functions $H$, $F$, $Q$ are given in the reference). Using Equation 2 for pure tension ($\sigma_t = \sigma$, $\sigma_b = 0$) the criterion Equation 1 has the form

![Figure 2. Complete FE model (a) of an edge crack with the crack tip region (b) in detail.](image-url)
with a safety factor \( s \), wall thickness \( w = 0.15 \text{ m} \) (special value for Konrad Type VI container), \( a/2c = 1/6 \), and \( \varphi = \pi/2 \) to maximise the right side of this inequality. The maximum stress \( \sigma \) results from the stress analysis of the unflawed cask. The consideration of pure tension is conservative for our purposes because \( \sigma = \sigma_r + \sigma_n \geq \sigma_r + H \sigma_n \) for \( H \leq 1 \) which is valid for surface flaws \( (a \ll w) \), local effects \( (c/b \to 0) \), and standard aspect ratios \( (a/2c \leq 1/6) \). For this case a separation of the load stress into the tension and bending part is not necessary to simplify the method in case of non-steady state stresses\(^{(8)}\).

Further, it has been investigated whether it makes any sense to use the strictly static method described above under dynamic (i.e. time-dependent) loads. The calculation of the dynamic stress intensity factor of the semi-elliptical surface flaw (Figure 1(a)) would require the very extensive numerical solution of a dynamic three-dimensional crack problem. On the other hand, the dynamic behaviour may also be evaluated in the special case \( a/c \to 0 \) to transform the semi-elliptical surface flaw into an edge crack in a plate (Figure 1(b)). This symmetrical two-dimensional crack problem under plane strain conditions was solved by means of the finite
element code ABAQUS. One half of the y-z plane was meshed with 8-node biquadratic continuum elements (CPE8R) with reduced integration (Figure 2(a)). In the y direction the model is infinite by means of special finite elements (CINPE5R). The z dimension arises from the plate thickness w. The ductile cast iron is assumed as linear-elastic with Young’s modulus of $E = 162,500$ MPa, Poisson’s ratio of $v = 0.29$, and the mass density is $7000 \text{ kg.m}^{-3}$.

A basic idea of this evaluation model is that the load stress is applied not remotely as tension load (analogous to Newman and Raju), but directly on the crack face as a pressure load. Both procedures are equivalent in case of elastic material behaviour. Hence, at the start of the simulation the calculation of propagating load stress waves from a remote boundary through the specimen to the crack tip is avoided. The infinity of the plate guarantees that no undesirable reflected stress waves load the crack tip. A detail of the finite element mesh around the crack tip, with collapsed 8-node parametric elements, is shown in Figure 2(b). The accuracy of the numerical solution was evaluated by comparison with the exact analytical solution of a semi-infinite crack in an infinite body which is valid until the first dilatational stress wave, reflected from a free surface of the finite model, arrives at the crack tip.

Figure 3 illustrates the dynamics of different load cases. The above mentioned analytical solution increases continuously. It is important to note that the stress intensity factor does not follow the increase of the applied stress immediately because of the gradual reaction of the crack tip stress fields. The natural bound-

![Figure 5](image-url)  
**Figure 5.** Critical flaw depth $a_c$ as a function of the applied stress $\sigma$ and the fracture toughness $K_I$ of the material. (Safety factor $s = 1.0$) $w = 0.15 \text{ m}$, $a/2c = 1/6$, $R_{p0.2} = 330 \text{ MPa}$.  

![Figure 6](image-url)  
**Figure 6.** Critical flaw depth $a_c$ as a function of the applied stress $\sigma$ and the fracture toughness $K_I$ of the material. (Safety factor $s = 1.41$). Other values as Figure 5.
aryes of a plate lead to an oscillating behaviour of the dynamic stress intensity factor converging to the value for static load conditions. Hence, rapid increases in the loads cause dynamic values temporarily greater than the static value. Therefore, a static analysis of such a crack problem would not be conservative. The third curve in Figure 3 represents the dynamic stress intensity factor due to the time-dependent load in case of the 5 m drop of a cubic container onto a reinforced concrete target which increases much more slowly and does not show any oscillations.

Figure 4 shows the numerically calculated function of the dynamic stress intensity factor for this accident scenario until 5 ms in comparison with a curve that was calculated with the static Newman and Raju equation for the corresponding geometry, and with the same load stress inserted. Obviously, the crack tip stress fields follow immediately a load stress with a rise time in the range of milliseconds. Differences between the curves are rather low (point A) and mostly negligible. Even if the prerequisites of the empirical solution are violated in the finite element model using a reflecting boundary condition in the y direction (finite plate), then the curves are still quite similar.

CONCLUSIONS

With the condition \( K_{I,\text{mat}} = K_{I,\text{app}} \) a non-linear equation arises from Equation 3, to determine the size of the critical flaw that must be prevented during the manufacturing process, or detected by non-destructive testing methods and procedures. The equation was solved numerically by a Newton method with the parameters given in Figure 5. In addition to the safety analysis of a given critical flaw, the safety performance of a cask design and of the material quality can be estimated. The necessary consideration of a safety factor leads to a reduction of the critical flaw size (Figure 6).

The investigations showed that the identification of separate tension and bending loads seems to be inappropriate for complicated cask structures, as well as highly time-dependent loads. Therefore, the maximum major principal stress (within the unflawed cask) should be used as a single load parameter for the fracture mechanics safety assessment. This procedure is especially well suited for a numerical safety analysis. The assessment for flaws at hollow grooves of the cask structure is currently investigated and requires the extension of the method to a more appropriate consideration of elastic–plastic failure phenomena.

The application of well-known 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’, 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 and Raju solution are not violated in our application. Therefore, any use of static equations with time-dependent parameters must be tested intensively in each case.

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REFERENCES