The Application of Fracture Mechanics to the Safety Assessment of Transport Casks for Radioactive Materials

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Abstract

BAM is the German responsible authority for the mechanical and thermal design safety assessment of packages for the transport of radioactive materials. The assessment has to cover the brittle fracture safety proof of package components made of potentially brittle materials. This paper gives a survey of the regulatory and technical requirements for such an assessment according to BAM's new "Guidelines for the Application of Ductile Cast Iron for Transport and Storage Casks for Radioactive Materials". Based on these guidelines higher stresses than before can become permissible, but it is necessary to put more effort into the safety assessment procedure. The fundamentals of such a proof with the help of the methods of fracture mechanics are presented. The recommended procedure takes into account the guidelines of the IAEA Advisory Material which are based on the prevention of crack initiation. Examples of BAM's research and safety assessment practices are given. Recommendations for further developments towards package designs with higher acceptable stress levels will be concluded.

1 Introduction

The transportation of radioactive materials from nuclear power plants has been a state-of-the-art technology for many years according to the transportation regulations which base in Germany on the IAEA Regulations [1]. The used transport casks have safety functions with regard to the prevention or limitation of the release of radionuclides from packages, to the shielding of the gamma and neutron radiation as well as to the prevention of nuclear chain reactions. These safety functions must remain unchanged also under severe accident conditions (Fig. 1). Therefore, the safety assessment procedure for the package must include the proof against failure by fracture if components of the cask are made of potentially brittle materials like ductile cast iron (DCI).

Fig. 1. 9 m drop with the POLLUX cask

BAM as the German responsible authority has published a safety assessment concept for transport casks made of ductile cast iron for the first time in 1985 [2, 3]. This concept contained essentially a limitation of the maximum permissible stresses and defined the permissible material properties. Since this time the use of DCI casks has nationally and internationally expanded very strongly. The internationalization was also the reason that the Advisory Material for the IAEA Regulations for the safe transport of radioactive material was supplemented with an appendix which contains recommendations for the safety assessment of cask components against failure by brittle fracture [4].

The remarkable distribution of ductile cast iron as material for Type B packages can be surely put down to the evolution of the casting technology and the improvement on the safety relevant material properties especially at thick-walled castings. On the whole the material quality at the serial production of casks has improved considerably since the publication of the first safety concept [5]. Particularly the deformation limits of the material could be improved fundamentally. The material properties are distributed more homogeneously over the wall thickness today.

In the course of time the cask designs were optimized more and more on the part of the manufacturers. These optimizations have led to a rise of the stresses appearing in the cask structure. So the prerequisites for a safety assessment of casks according to the old strategy could increasingly be satisfied only with very lavish impact limiters. This situation resulted in the formulation of new “Guidelines for the Application of Ductile Cast Iron for Transport and Storage Casks for Radioactive Materials” by BAM in 2002 [6]. According to these guidelines higher stresses than before can be permitted. However, a comprehensive safety proof based on the methods of fracture mechanics is required for that. The essential features of such a fracture mechanics safety assessment are explained in the following.

2 Evaluation Methods

The IAEA recommendations for the prevention of failure by brittle fracture are contained in the Appendix VI to the Advisory Material [4] for the IAEA Regulations. They are the result of the work of international experts who have summarized the worldwide level of knowledge in this field. On the basis of these recommendations the proof against failure by brittle fracture can be subdivided into three groups:

Ductile Materials

The undoubtedly simplest method is the use of a material which cannot fail by brittle fracture throughout the required service temperature range. The use of, for example, austenitic rolled or forged steels guarantees an extensive plastic deformation and ductile crack propagation before a plastic collapse. A brittle fracture with a crack propagating unstably can be excluded. A limitation of the stress level or the absence of material defects are not necessary or are achieved by other conditions, e.g. the limitation of the deformation to ensure the tightness of the cask.

T_{NDT} Approach

The second method is based on the investigation of the arrest of a propagating crack in dependence of the temperature by means of the drop weight test. This correlation addresses, for example, ferritic steels, for which there are substantial databases relating impact energy (Charpy testing) to fracture toughness. In such cases, the Charpy impact energy can be used as an indirect indicator of material toughness. This approach may be used for a variety of high quality carbon and carbon-manganese steels.

Fracture Mechanics Assessment

The third method requires the limitation of the highest mechanical stresses under accident conditions by a corresponding design of the casks and the limitation of the size of material defects by non-destructive examination of the structure. By these measures a crack initiation and consequently brittle fracture can be precluded. We find examples for this method in the standards of different states for the construction of nuclear components. These are generally based on the laws of the linear-elastic fracture mechanics, however with differences between the individual codes e.g. regarding the safety factors. In comparison with the design of nuclear components it must be noted for the application to transport casks, that both the stress level and the loading rate can be locally higher at drop or puncture tests. This difference must be taken into account at the examination of the material behaviour. For the application of this assessment method it is required, that the package designer analyses in detail the interaction between postulated material defects in the packaging, the stress in worst case situations, the fracture toughness and the deformation properties (yield stress, tensile strength, elongation at fracture) of the used material.

3 BAM Safety Assessment of DCI Casks

The BAM safety assessment concept bases on the recommendations of the IAEA [4] proceeding from the principle of preclusion of crack initiation and consequently of stable or unstable crack propagation for postulated crack-like material defects.

The methods of the linear-elastic fracture mechanics (LEFM) have to be used at the fracture mechanics safety analysis if the plastic deformations remain restricted to the range of the process zone defined by the LEFM. If the limitations of the linear-elastic fracture mechanics are not met because of an elastic-plastic material behaviour, then the fracture mechanics safety analysis has to be carried out by using characteristic quantities of the elastic-plastic fracture mechanics (EPFM).

For the safety analysis it is necessary to derive the loading rate from measured or calculated dynamic strains in the cask structure without material defects. Depending on this value the safety analysis must be carried out either for quasi-static or dynamic loading conditions and consequently with static or dynamic characteristic quantities and material properties. According to the present state of knowledge we assume, that strain rates $\dot{\varepsilon} \geq 0.1\ s^{-1}$ indicate a dynamic analysis.

The assessment of the safety against failure by fracture is made by a comparison of fracture mechanics load parameters with the fracture mechanics material properties characterizing the material resistance to crack initiation. The failure by brittle fracture is avoided if the stress intensity factor K_{appl}, which characterizes the load of the crack or material defect in the component, is smaller than the corresponding initiation material property K_{mat}. The failure by ductile fracture is precluded in an analogous way by the condition, that the value of the so-called J integral J_{appl} as load parameter is smaller than the corresponding initiation material resistance J_{mat}:

$$K_{appl} < K_{mat} \qquad \text{or} \qquad J_{appl} < J_{mat} \tag{1}$$

For a Mode I crack one gets under static loading conditions with the static load parameters ($K_{I,appl}$, $J_{I,appl}$) and static material properties (K_{Ic}, J_i)

$$K_{I,appl} \leq \frac{K_{Ic}}{S} \qquad \text{or} \qquad J_{I,appl} \leq \frac{J_i}{S} \tag{2}$$

and under dynamic loading conditions with the dynamic load parameters ($K^d_{I,appl}$, $J^d_{I,appl}$) and dynamic material properties (K_{Id}, J_{id}):

$$K^d_{I,appl} \leq \frac{K_{Id}}{S} \qquad \text{or} \qquad J^d_{I,appl} \leq \frac{J_{id}}{S} \tag{3}$$

The load parameter must represent an upper bound by the consideration of the most unfavourable geometry and orientation of the crack, the maximum applied stress and crack size as well as the loading rate. Therefore a detailed stress analysis is an essential prerequisite for the fracture mechanics safety analysis. The consideration of the type and size of the material defect leads to specifications for a reliable non-destructive examination (NDE) of the component to find material defects of critical size in all relevant parts of the package. A suitable safety factor for the load parameter has in addition to be taken into account for the coverage of inaccuracies and uncertainties in the stress analysis, the non-destructive examination and the fracture mechanics models. Its value has to be justified in detail.

The safety factor in eqn. (2) and (3) must be selected in a suitable way with these prerequisites in mind. As an example one gets for the proof of safety against brittle fracture under static loading conditions with the stress intensity factor for a Mode I crack

$$K_{I,appl} = Y\,\sigma\,\sqrt{\pi\,a} \qquad \text{and} \qquad a = a_{NDE} \tag{4}$$

the condition:

$$K_{Ic} \geq S_K \cdot Y \cdot S_\sigma\,\sigma \cdot \sqrt{\pi \cdot S_{NDE}\,a_{NDE}} \tag{5}$$

In eqn. (4) und (5) the variables have the following meanings:

- σ applied stress,
- a_{NDE} size of the material defect to be assessed by fracture mechanics (its existence has to be prevented by non-destructive examination),
- Y geometry function,
- S_σ safety factor for calculated stresses ($S_\sigma > 1$),

S_{NDE} safety factor for non-destructive examination (S_{NDE} > 1),
S_K safety factor which includes uncertainties at the measuring of the fracture toughness (K_{Ic}) of the material and at the calculation of the stress intensity factor ($K_{I,appl}$) which are not contained in S_σ and S_{NDE} ($S_K \geq 1$).

The safety factor S in eq. (2) is therefore determined by:

$$S = S_K \, S_\sigma \, \sqrt{S_{NDE}} \tag{6}$$

As the material property (K_{Ic} in our example) a lower bound must be defined under consideration of the material specification as well as the influence of the loading rate, the temperature and the wall thickness of the cask. For the determination of this property a reliable database is needed. The underlying data must also include material investigations at the highest loading rate in combination with the lowest temperature in use. Alternatively the material property can be found out for the individual case considering the mentioned boundary conditions. The toughness values from the material tests must cover the material properties of the later serial casks.

4 Determination of the Stresses

The compliance with the criteria, eqn. (2) and (3), for the safety against failure by fracture has to be shown in all safety relevant positions of the cask structure and at every time in the fracture mechanics safety analysis for a cask design. The value of the stress intensity factor or the J integral is the temporal and local maximum value deduced from all values along the crack front:

$$K_{I,appl} = \max\left\{K_{I,appl}(\vec{x},t)\right\} \qquad J_{I,appl} = \max\left\{J_{I,appl}(\vec{x},t)\right\} \tag{7}$$

or

$$K^d_{I,appl} = \max\left\{K^d_{I,appl}(\vec{x},t)\right\} \qquad J^d_{I,appl} = \max\left\{J^d_{I,appl}(\vec{x},t)\right\} \tag{8}$$

The computational fracture mechanics analysis of a cask containing a crack-like defect is made by simulation of the mechanical tests in accordance with the requirements of the regulations. The positions inside the cask structure with a high fracture mechanics load must be identified and assessed. These are primarily the positions with high stresses. Since the position of the highest stress is not necessarily the position of the highest fracture mechanics load, positions with lower stresses have to be included in the examination if required. The calculation of the fracture mechanics load parameter may be carried out either by

a) an analysis of the whole cask containing the crack-like defect or by
b) an analysis of a submodel with the crack-like defect and prescribed boundary conditions from the calculation of the whole structure.

The method a) is suitable for static as well as dynamic analyses. The convergence of the calculated stress intensity factors K_{appl} or J integral values J_{appl} must be shown, in the case of J integral values by various integration domains.

The method b) is allowed only for quasi-static crack problems, i.e. in cases where the influence of inertial forces on the stress field around of the crack tip is negligible. For the analysis of the crack configuration it is permitted to use formulae from stress intensity factor handbooks, but it is fundamental to prove the validity of such formulae also under the boundary conditions met here.

The applicability of static fracture mechanics solutions from compendiums of formulae for typical load scenarios at casks was proved by BAM at a special case [7]. The crack showed quasi-static behaviour despite a time-dependent, but adequately slowly changing load. It has to be emphasized that a generalization of these results to other load conditions without verification is inadmissible. However, in the shown way the validity of such approaches can be checked for dynamic load cases at casks.

Fracture mechanics solutions on the basis of single cracks in geometrically simple components are frequently valid only in the crack opening mode I. They cannot always be transferred to the conditions in real cask structures because more complicated loads appear e.g. in corners and edges. An intensive verification of the stress states, of the applicability of the crack model, and of the accuracy of possible conservative estimates is therefore necessary. Possibly the results must be justified by the calculation of dynamic stress intensity factors or J integral values.

The suitability of the calculation models, calculation procedures and computer programs for the investigation of the dynamic processes during a cask drop test as well as the qualification of the employees have to be proved. Notes on safety analyses by means of numerical methods can be found in the BAM Guidelines for the Numerical Safety Analyses for the Approval of Transport and Storage Casks for Radioactive Materials [8].

5 Material Defects

The definition of the size of crack-like material defects is contained in test specifications for the non-destructive examination of cask components. The “reference size” is the postulated crack size used for analyses purposes. The “rejection size” is a crack size which would fail to meet quality assurance requirements. The “critical size” is that size which would potentially initiate an unstable crack growth. For safety analyses or demonstrations the reference crack should be placed at the surface of the package at the location of the highest applied stress. The precision of the procedure for the non-destructive examination has to be assessed by a safety factor.

6 Validity Issues

The fracture toughness of ductile cast iron is influenced by the microstructure and the load parameters (like temperature and strain rate) as well as the geometry of the component or specimen and constraint conditions [5, 9]. The suitable fracture mechanics concept must be selected in dependence of the significance of the ductile behaviour of the material. The J integral concept is usable both in the validity range of the linear-elastic fracture mechanics and the elastic-plastic fracture mechanics. On the other hand, the stress intensity factor concept (or K concept) is valid only for linear-elastic material behaviour. Contrary to the always permitted conversion of fracture toughness values K into J integral values, the reverse conversion of J values into fracture toughness values K_J is permitted only for small inelastic deformations in the vicinity of the crack tip (small scale yielding). Otherwise a non-conservative overestimation of permitted stresses or sizes of material defects is possible [10].

Fracture mechanics properties under dynamic loading conditions are determined analogous to static loading conditions on the basis of the standards ASTM E 399 (linear-elastic) as well as ESIS P2 or ASTM E 1820 (elastic-plastic). Quasi-static conditions are assumed for strain rates $\dot{\varepsilon}$ < 0,1 s^{-1}. In dependence of the loading rate which is relevant for the investigated load scenario, static or dynamic fracture mechanics material properties must be found out and used.

The measuring of static fracture toughness values K_{Ic} or dynamic fracture toughness values K_{Id} in the validity range of the K concept of the linearly-elastic fracture mechanics requires the test of sufficiently large specimens. This means an increased effort in the practice. In the context of the approval of casks the measuring of material properties is generally carried out at small specimens. The small size of the specimens and the elastic-plastic material behaviour of ductile cast iron require therefore the application of the J integral concept with the determination of the crack resistance curve (J - Δa or J_d - Δa) and of static or dynamic ductile initiation values according to the standards ESIS P2 (J_i or J_{id}) and ASTM E 1820 (J_{Ic} or J_{Id}).

7 Material Properties

As a result of extensive investigations of ductile cast iron in the context of DCI cask approvals, a lower bound quasi-static fracture toughness of K_{Ic} = 50 MPa·$m^{1/2}$ was defined for the lowest service temperature of -40 °C for cast iron qualities according to the BAM safety concept [2].

In comparison with the fracture mechanics characterization of cask materials under static loading, there are fracture mechanics analyses of the correlation between material quality and fracture properties under dynamic loading conditions only for small specimens [5, 9]. A significant reduction of the fracture toughness does not have to be expected for static loads down to temperatures of approximately -70 °C if the requirements for the material quality from the BAM safety concept [2] are met. However, under dynamic loading conditions the transition region of the fracture toughness is passed in the temperature range from -20 °C to -40 °C. The crack initiation toughness of DCI can decrease on comparatively low values because of the changing of the failure mode from ductile to brittle fracture. In the lower shelf of the fracture toughness, K_{Id} values below 50 MPa·$m^{1/2}$ down to 30 MPa·$m^{1/2}$ can be found [11].

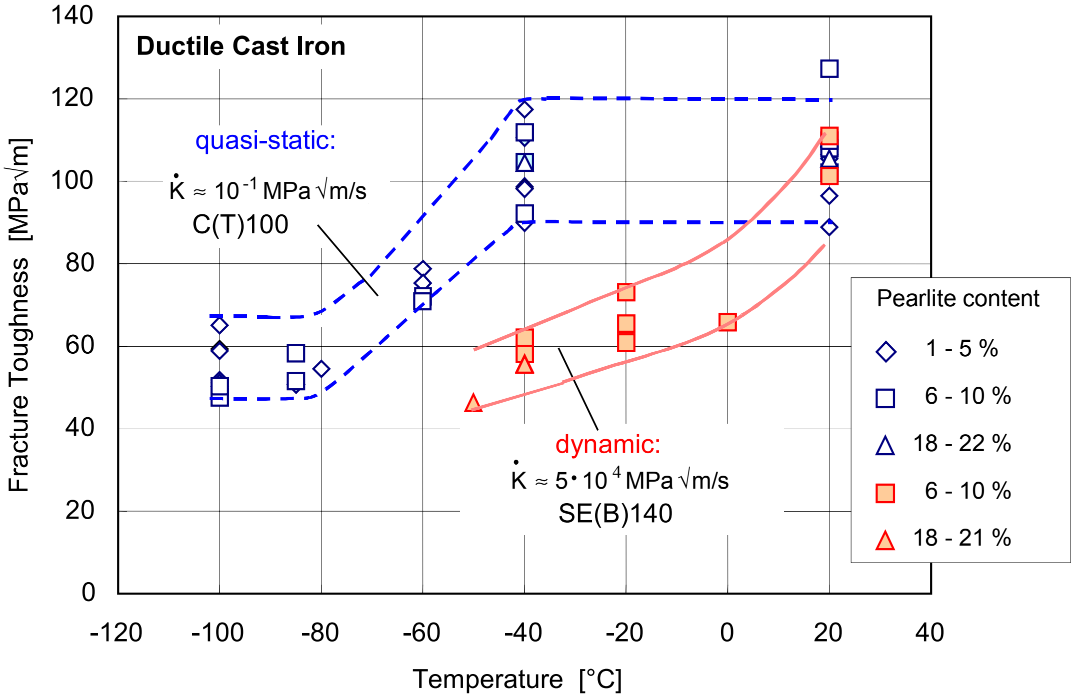

Fig. 2. Influence of loading rate, test temperature and pearlite content on the fracture toughness behaviour of ductile cast iron according to [13, 14]

BAM investigated bending specimens of type SE(B) 140 from container walls to find the dynamic fracture toughness for large specimens [12]. The loading rate reached $\dot{K} \approx 10^4$ MPa·m$^{1/2}$/s in these impact bending tests. The characterization of the microstructure of the investigated DCI showed mean pearlite contents up to 20 %. The transition range was found in the temperature range from -40 °C to 22 °C. The minimum value of the fracture toughness of 50 MPa·m$^{1/2}$ could be confirmed for the investigated large specimens also under dynamic loading conditions (Fig. 2). Further investigations are required because of the small number of investigated specimens and the small database of available toughness values for large specimens.

8 Examples

In the past there were several international research programmes on the one hand for the characterization of ductile cast iron as cask material and on the other hand for tests also under extreme mechanical loading conditions beyond the requirements of the IAEA regulations. Some of these investigations shall be mentioned here (references can be found in [6]):

- 9 m drop of CRIEPI, Japan, with an original cask for spent fuel (comparable with the large German CASTOR V cask) at a temperature of -40 °C with an artificial crack-like defect of critical size onto an unyielding IAEA target,
- 9 m drop tests of SANDIA National Laboratories, USA, and a critical drop test from a height of 18 m with a cooled MOSAIK cask with an artificial crack-like defect onto steel rolls located on an unyielding IAEA target,
- drops tests of BAM from heights up to 14 m with a CASTOR VHLW cask with a large artificial defect onto steel rolls located on an unyielding IAEA target,
- drop tests of BAM from heights up to 9 m with a thick-walled pipe of ductile cast iron (corresponding to the 1:2.5 scaled model of a large cylindrical CASTOR V cask), equipped with an artificial crack-like defect, onto rolls located on an unyielding IAEA target,
- 9 m drop test of BAM with a CASTOR MTR cask at -40 °C with an artificial crack-like defect onto the unyielding IAEA target,
- drop test of BAM with a cooled DCI container Type VI with 5 artificial crack-like defects onto a real target representative for the foundation in a final storage facility,
- drop tests of GNS with MOSAIK casks from 800 m height onto a concrete runway.

These investigations have demonstrated that casks made of ductile cast iron can withstand also extreme loads without failure by fracture. However, a necessary prerequisite for the acceptance of high maximum stresses in the structure of transport casks is a fracture mechanics safety analysis as illustrated here.

9 Conclusions

Within the last 25 years the manufacturers of the casks have managed to reach the duplication to triplication of the transported masses of spent fuel per cask. In the future a further increase of this ratio is affected to a great extent also by the development and optimization of the parameters which influence the fracture mechanics assessment, e.g. the size of material defects, the loading rate, the fracture toughness and the calculation methods.

A remarkable increase of the ductility at a nearly equal level of the material strength has to be noticed at the cask materials in the same time period. A further increase of the mechanical stresses in the cask structure, for example by other materials like steel, does not seem conceivable. A progress can be seen in the determination of the stresses by the use of more realistic models. The safety margin of conservative assumptions especially for ductile cast iron must be analysed and can possibly be reduced by refined calculation methods. Further improvements of the cask constructions and of the safety assessment methods are necessary.

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