A NEW FRACTURE MECHANICS ASSESSMENT METHOD FOR FERRITIC STEEL COMPONENTS OF TYPE B PACKAGES

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SUMMARY

The IAEA Regulations for the Safe Transport of Radioactive Materials require the consideration of temperatures of -40 °C for Type B package designs. According to the German approval practice, this temperature shall be also taken into account during mechanical tests simulating accident situations with these packages. Therefore, the necessary safety analysis includes fracture mechanics assessments for all safety related components of the packages. In the past, these evaluations have been performed for components manufactured from ferritic steels by methods usually used for pressure vessels. Because of the restrictions of these methods if applied to thick-walled casks and the low-temperature embrittlement of ferritic steels which is additionally increased by high impact rates during accidents, BAM as the responsible German testing authority for Type B packages required the establishment of a fracture mechanics analysis method that considers especially the test conditions for this package type. A proposal of the German cask designer Gesellschaft für Nuklear-Behälter (GNB) provides the use of a method for these analyses which has been developed during the recent years in the European Communities for steel constructions (especially bridges) with the objective to establish an appropriate European standard. The paper discusses problems and necessary adaptions of the method if applied to Type B packages from the point of view of the testing authority.

INTRODUCTION

In the past, fracture mechanics assessments for Type B shipping cask components manufactured from steels were performed in Germany by methods usually used for pressure vessels. This practice had primarily administrative reasons but it does not cause substantial difficulties as long as thin-walled ferritic components are concerned or components manufactured from austenitic or semi-austenitic steels. Because of the low-temperature embrittlement of ferritic steels which is additionally increased by high impact rates expected during accidents, more precise and scientific founded fracture mechanics analyses are necessary for thick-walled ferritic steel components.

During the last years, investigations have been performed in the framework of an European project with the objective to establish an European standard for fracture mechanics assessments of steel constructions like bridges, etc. These investigations were coordinated by the Institutes for Steel Construction and for Ferrous Metallurgy of the Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen. Result of these investigations is a fracture mechanic based concept to avoid brittle fracture of structural parts which considers besides other important parameters the influence of dynamic loading conditions on stress intensity factors *(Eurocode 3, 1997)*. It was the proposal of the Gesellschaft für Nuklear-Behälter (GNB) to examine the applicability of that or an adapted method also for fracture mechanics assessments of ferritic steel components of shipping casks for radioactive material. On account of questions expected in this context, BAM as the competent testing authority for Type B shipping casks in Germany was involved in an early phase of this process.

BASIS OF THE ASSESMENT METHOD

The method proposed for fracture mechanics assessments of steel constructions with surface cracks, the scientific base of that method and the prerequisites for its application are described in the draft of the background documentation of the Eurocode 3 "Design of Steel Structures", Part 2 - Bridges, Document No. II.3.1 "Choice for steel material to avoid brittle fracture". Detailed fundamentals and the engineering adaption of the Eurocode method considering the requirements to ferritic steel components of Type B packages are discussed in the paper of Sedlacek et al. *(1997)* presented to this conference. For that reason, the following explanations are restricted only to the most important characteristics of the method.

The Eurocode method is a concept of fracture mechanics evaluation for ferritic steels with a specified Charpy -V- energy of 27 J at a defined test temperature (e.g., T_{27J} = -40°C) against brittle fracture. These requirements to the Charpy energy are connected with a fracture mechanic safety analysis. Safety against brittle fracture is proved if the design value of the temperature action (design temperature T_{Ed}) is equal or greater than a temperature which describes the resistance of a structural detail to brittle fracture considering the material toughness (T_{Cd}):

$$T_{Ed} \geq T_{Cd} \qquad (1)$$

T_{Cd} is the sum of four terms,

$$T_{Cd} = T_{100} + \Delta T_f + \Delta T_v + \Delta T_a \qquad (2)$$

T_{100} is the temperature at which the materials toughness K_{Jc} amounts to 100 MPa*$m^{1/2}$. The other terms consider necessary temperature corrections caused for surface cracks by the applied stress (ΔT_f), by the strain rate (ΔT_v), and by the statistically evaluated inaccuracy of the used brittle fracture model (ΔT_a).

All critical fracture mechanics parameters, e.g. crack dimensions, applicable stresses and strain rates, may be derived from equations (1) and (2). The special objective of the application described in this paper is the determination of a critical, i.e., maximum allowed crack size.

At present, BAM examines the applicability of the Eurocode method for fracture mechanics assessments of ferritic steel components of Type B packages. Without final decisions with regard to all prerequisites and assumptions which must be fulfilled, BAM is of the opinion that the method seems basically suitable for proof of safety of Type B cask components against brittle fracture. Nevertheless, there remain questions which must be answered before final acceptance. Moreover, it was to examine if parts of the method must be adapted to consider the special conditions prescribed for Type B shipping casks testing. In this context, the compatibility of the method with the recommendations of the Appendix VI of the Draft IAEA Material No. ST-2 *(IAEA, 1997)* must be checked.

QUESTIONS TO BE ANSWERED

Reasons for the discussions concerning the transferability and the subsequent use of the Eurocode method for Type B safety analyses are primarily the differences between the design criteria and loading conditions of usual steel contructions and Type B packages. Such questions identified by BAM are:

(Q1) Which general limitations must be considered in consequence of different material requirements for steel constructions and Type B packages ?

(Q2) Which limitations must be taken into account with respect to the maximum primary stresses ?

(Q3) Steel constructions like bridges are subjected to quasi-static and more or less cyclic loading conditions. In comparison with that, Type B packages shall survive dynamic impact loads with very large strain rates. Is it allowed to use the Eurocode method and is the method verified also for these conditions ?

(Q4) The Eurocode method has been developed for constructions (plates) with wall thicknesses which are generally lower than those for Type B cask components. Moreover, the data basis is rather low. Is an application of the method allowed for wall thicknesses which can be in maximum 600 mm ? Is the correction equation used by the method to quantify the influence of the wall thickness on the yield strength adequate to the values of the yield strengths given in German and European standards ?

(Q5) Which inaccuracies of testing data are covered by the value of the safety item ΔT_a recommended by Dahl et al. *(1997a)* for Type B shipping cask materials ?

(Q6) How to quantify the safety item ΔT_a in eq. (2) with consideration of the recommendations of the Appendix VI of the Draft IAEA Material No. ST-2 *(IAEA, 1997)*. This guide requires a safety factor of $s_t = K_{I,mat}/K_I$ against the lower bound fracture toughness ($K_{I,mat}$) of the material. (For accident analyses, a factor $s_t = 1.4$ is recommended. K_I is the applied stress intensity factor.)

(Q7) Other Codes, e.g., *ASME (1992)*, distinguish between bending and membrane stresses and consider both parts in calculating the stress intensity factors. How should be considered both types of stresses and, moreover, two- and three-dimensional stress conditions if the Eurocode method is applied ?

The answers to these questions which can be given at present on the basis of still running discussions with the above mentioned Eurocode 3 coordinators are as follows:

(A1) The Eurocode method can be used for ferritic mild steels within a yield strength range between 200 to 1000 MPa provided that the correlation between the Charpy -V- energy and the fracture toughness corresponds to that supposed in the Eurocode. The method is not applicable for materials like ductile cast iron which is also used for Type B casks in Germany.

(A2) Considering the results of investigations of the Eurocode 3 coordinator (*Dahl et al., 1997a*, Annex II), failures occured scarcely if the applied stresses were lower then 90 % of the yield strength ($Rp_{0.2}$) and if the stress intensity factors were lower then $0.85^* K_{Ic}$. Therefore, a limit of 0.8* $Rp_{0.2}$ seems to be an acceptable upper limit for the applied stress including possibly an additional safety margin. A final decision with regard to the maximum allowed stress is outstanding but must also take into consideration the necessary limitation of component deformations. In this context it should be kept in mind that the method may not be applied if the stresses exceed the yield strength of any material significantly.

(A3) The Eurocode method includes an empirical equation that describes the dependence of the transition temperature on the strain rate. According to investigations of the Eurocode 3 coordinator *(Dahl et al., 1997a)*, this equation is experimentally verified for strain rates up to 30 s^{-1}, i.e., strain rates much larger than expected according to the experience with German shipping cask designs.

(A4) On principle, the equation for a specified thickness correction factor used in the Eurocode method is verified by experiments performed for thicknesses of plates lower than about 150 mm. According to Dahl et al. (*1997b*), the model is also applicable to thick-walled components up to wall thicknesses which are of interest for Type B casks.

A comparison of the yield strength values calculated by the equation recommended in the Eurocode 3 with values given in German standards for ferritic steels shows a non-uniform image (Figure 1). In order to avoid problems one should use either standardized values or values stipulated in released (in Germany by BAM) materials specifications.

(A5) It is not clear which inaccuracies of materials properties and materials testing data are covered by ΔT_s and how to determine this item exactly. This question must also be seen in the context with question (Q6), see answer (A6) .

(A6) Sedlacek et al. (*1998*) recommend a value of 20 K for the safety item ΔT_s in eq. (2) and the calculation of ΔT_f (which considers the effect of the applied stress) by eq. (3):

$$\Delta T_f = 52 * \ln\left[\frac{(K_{I,mat} - 20) * k_t - 10}{70}\right] \qquad (3)$$

Eq. (3) reflects an averaged curve of the dependence of the fracture toughness of the material ($K_{I,mat}$) on the temperature.

In order to check that approach, BAM has compared the results obtained by it with those calculated with consideration of a safety factor of s_t=1.4 using eq. (4) with ΔT_s=0 (shortened "AVM" in figures 2 ... 4) instead of eq. (3) with ΔT_s=20 K ("LBM"):

$$\Delta T_f = 52 * \ln\left[\frac{(s_t * K_I - 20) * k_t - 5.235}{36.644}\right] \qquad (4)$$

This approach considers the requirements of the IAEA guide *(IAEA, 1997)* formally (i.e., from the mathematical point of view) in a more exact manner, provided that it is possible to regard the used Master Curve as a lower bound curve for ΔT_f. This curve reflects a 5 % failure probability of the test specimens *(Sedlacek et al., 1998)*.

Figures 2 and 3 show that the values for allowable crack depths calculated by the approaches "AVM" and "LBM" differ strongly from each other. On the one hand, the crack depths calculated with the second ("LBM") approach seem to be rather conservative. On the other hand, there is no evidence that the crack depths calculated by the first ("AVM") approach includes the required safety margin. It can be shown, e.g., that the first approach is also not equivalent to an approach using eq. (4) with $s_t=1.0$ in combination with a safety item $\Delta T_a=0$: The allowable crack depths calculated with these assumptions are also lower then those calculated by eq. (3) and $\Delta T_a=20$ K. Therefore, the discussions with regard to the establishment of an adapted Eurocode method with an adequate safety term are not yet finished.

(A7) The Eurocode method does not distinguish between bending and membrane stresses. It interpretes the stresses always as membrane stresses. In principle, this is a conservative approach. This can be demonstrated generally, and also by calculations with other codes discussed in next chapter. This approach is acceptable also for Type B cask safety analyses.

For thick components with two- or three-dimensional stress distributions, the stress component perpendicular to the crack area at the tip of the crack should be taken into consideration.

RESULTS OF PARAMETRIC STUDIES WITH THE EUROCODE METHOD AND OTHER CODES

The objective of studies performed with the Eurocode method was, on the one hand, to recognize the sensibility of the results obtained with the method about important input parameters, and, on the other hand, a comparison with results of other codes. Furthermore, the studies should help to clarify how to consider the safety factor ($s_t = K_{I,mat}/K_I$) recommended in *(IAEA,1997)* by the method. The analysis was performed by an own computer routine (BRIFRAC) that allows in the first step the calculation of the maximum allowed crack depth by the Eurocode method for given component, crack and material specifications. Secondary result of this step is the stress intensity factor for that crack. Considering it as a given value, the maximum allowable crack depths are than calculated by other methods *(ASME 1992, Newman and Raju, 1981)*. One have to keep in mind here that both the ASME and the Newman/Raju methods do not take into consideration dynamic loads but more or less steady state conditions. Therefore, the comparison can be only a qualitative one and the results obtained with the ASME and Newman/Raju methods may not be used for other purposes.

The paper presents results of calculations which were performed for steel TStE 355. The axis ratio of the semi-elliptic surface crack was 0.33. Two cases were distinguished with regard to the applied (primary) stresses: fsig= 0.7 and fsig=0.6 (70 and 60 % of the yield strength). The secondary stresses (e.g., thermal stresses) were assummed to be 50 MPa. The calculations with the ASME and Newman/Raju method were carried out for two specified cases characterized by an interpretation of the applied stress either as bending or as membrane stress. If the applied stress was supposed to be a bending stress, the conditions at the tip of the crack were considered (parametric angle of the ellipse $\Phi = 90°$).

Figures 2 and 3 show the results obtained with consideration of two different safety approaches. Conclusions from these results are discussed in the preceding section. It should be mentioned in this context that the safety factor of 1.4 is equivalent to safety terms $\Delta T_a = 55...65$ K in the examples presented here. Figure 2 demonstrates that the influence of the applied stress on the maximum allowed crack depths is rather large. Contrary to that effect, the variation of the strain rate by a factor of 2 (Figure 3) shows nearly negligible effects. With respect to the results obtained by the ASME and Newman/Raju method, it is obvious that missing dynamic, i.e., $K_{I,mat}$ reducing effects, explain the larger differences if compared with the Eurocode results. The curves calculated with the assumption that the applied stress is a bending stress deviate for small wall thicknesses qualitatively from all other curves. This is a consequence of the supposed linear bending stress function in the wall and the decreasing distance between the tip of the crack and the neutral zone.

CONCLUSIONS

The paper discusses questions arising from the intended application of a method *(Eurocode 3, 1997)* developed for the fracture mechanics assessment of components of steel constructions to Type B cask safety analyses. This seems to be possible with some adaptions if some prerequisites deliberated in the paper are fulfilled. However, a final decision concerning the applicability of the method in the framework of approval procedures requires a further verification of the method for all parameter ranges of interest for Type B packages.

REFERENCES

ASME Boiler and Pressure Vessel Code, Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components, Appendix A, *Analysis of Flaw Indications*, 1992 Edition

Background documentation to Eurocode 3 Design of Steel Structures Part 2 - Bridges; Document No.: II.3.1, Choice for steel material to avoid brittle fracture, Draft, Aachen, May 1997

Dahl, W., Langenberg, P., Sedlacek, G., Stranghöner, N., *Anpassung des Sprödbruchsicherheitsnachweises des Eurocode 3, Anhang C, an Deckel von Nukleartransportbehältern,* RWTH Aachen, Juli 1997 (1997a)

Dahl, W., Langenberg, P., Sedlacek, G., Stranghöner, N., *Ergänzung zur Stellungnahme zu den Anmerkungen der Bundesanstalt für Materialprüfung (BAM) in Berlin zum Anpassungsdokument für den Sprödbruchsicherheitsnachweis für ferritische Deckel*, RWTH Aachen, August 1997 (1997b)

Eurocode 3, Design of Steel Structures, Part 2, Steels Bridges, Draft ENV 1993-2 (September 1997)

IAEA Safety Standards Series No. ST-2, *Advisory Material for the Regulations for the Safe Transport of Radioactive Material (1996 Edition)*, Draft for TRANSSAC, International Atomic Energy Agency, Vienna, 1997

Newman, J.C., Raju, I.S., *An Empirical Stress Intensity Factor Equation for the Surface Crack,* Engineering Fracture Mechanics, Vol. 15, No. 1-2, pp.185-192, 1981

Sedlacek, W., Dahl, W., Langenberg, P., Stranghoener, N., Dreier, G., Diersch, R., *Application of a Fracture Toughness Analysis for Ferritic Steel Components of Transport and Storage Casks Using an Adapted Eurocode 3 Approach*, Conference paper, PATRAM '98, 1998

Figure 1: Yield strength vs. wall thickness; DIN 17103 and Euronorm correlation; steels TStE 355 and 460

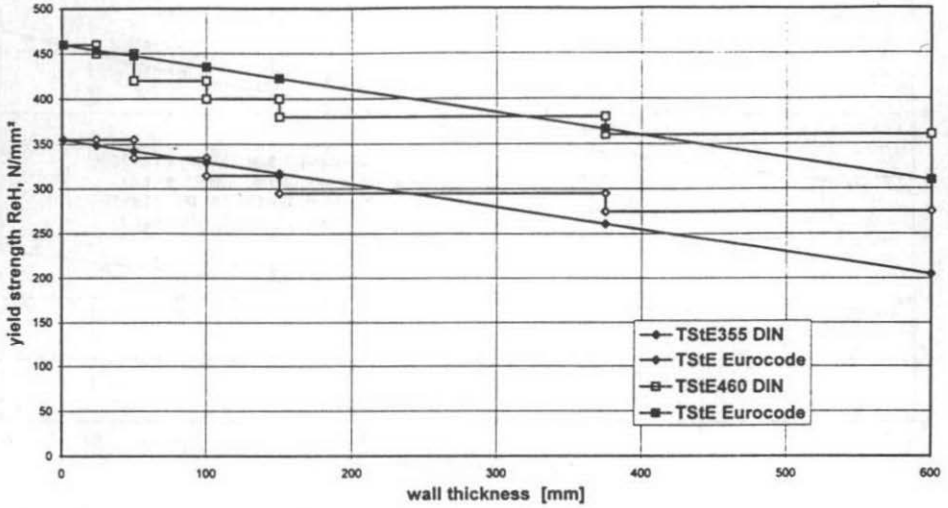

Figure 2: Maximum crack depth calculated by the EUROCODE method; influence of safety approach and primary stress level; TStE 355, eps = 0.1 [1/s], sigs = 50 [N/mm²]

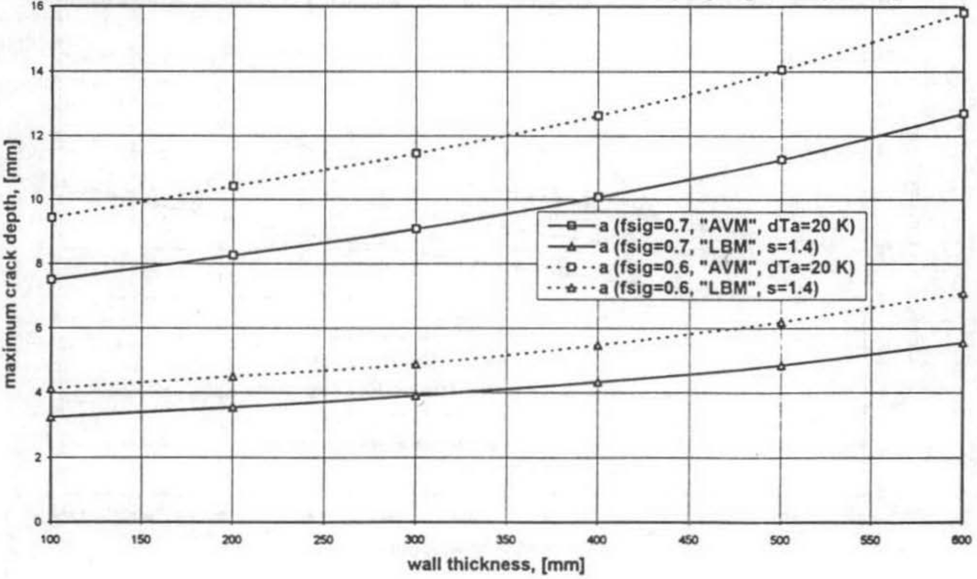

Figure 3: Maximum crack depth calculated by the EUROCODE method; influence of safety approach and strain rate; TStE 355, fsigp=0.7, sigs = 50 [N/mm²]

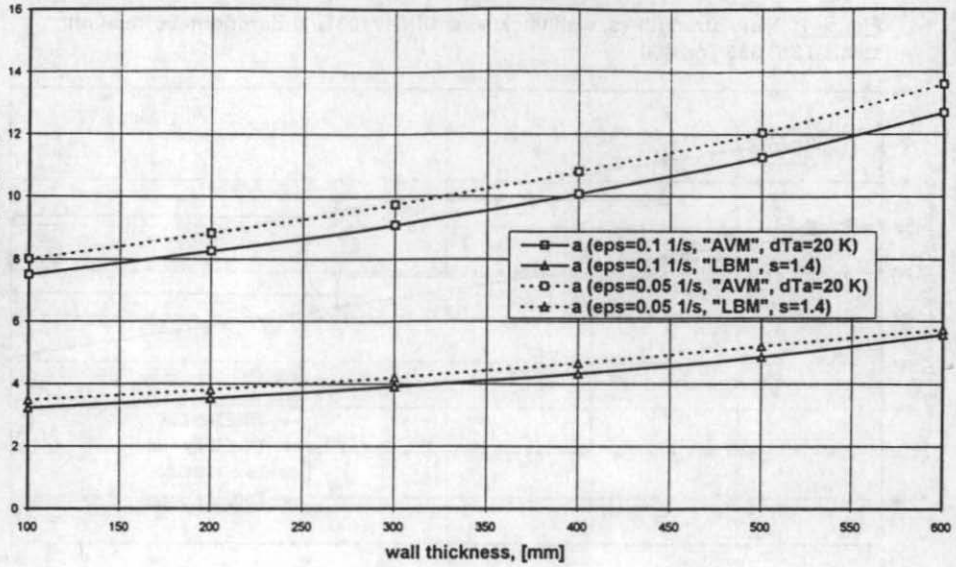

Figure 4: Maximum crack depth calculated by the EUROCODE, ASME and Newman/Raju methods; TStE 355, eps = 0.1 [1/s], fsig = 0.7, sigs = 50 [N/mm²]; "mean value" master curve ("AVM"), dTa = 20 K