APPLICATION OF A FRACTURE TOUGHNESS ANALYSIS FOR FERRITIC STEEL COMPONENTS OF TRANSPORT AND STORAGE CASKS USING AN ADAPTED EUROCODE 3 APPROACH

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SUMMARY

The choice of a structural steel material for a component of a transport and storage cask for RAM is strongly determined by the demand that the cask has to withstand a free fall from 9-m-height without losing its integrity and leak tightness. In terms of fracture mechanics this means that instable crack growth must not occur even under the conditions of high amplitude dynamic loading at temperatures of -40 °C.

In the course of harmonisation of European design guidelines, the Eurocode 3 has been developed which contains a fracture mechanic based concept for the steel selection to avoid brittle fracture, called Annex C. This method combines fracture mechanics tools like the failure assessment diagram (CEGB-R6-procedure) with fracture mechanics life time assessment procedure for fatigue loaded structures. The required toughness in terms of the stress intensity factor K_I is related to the T_{27J} charpy transition temperature by means of a master curve and by a correlation between the fracture mechanics transition temperature T_{K100} and the charpy transition temperature T_{27J}. Both relations have been proved to be valid for stuctural steels in the range of 235 to 960 MPa yield strength. Besides that a semiprobabilistic safety approach that takes account of the model inaccuracies by calibration of large scale tests has been applied to derive a safety element for a risk of failure of $p_f = 10^{-5}$.

The fracture mechanic concept of Eurocode 3 has been adopted to calculate critical failure lengths for lids made from ferritic steels of transport and storage casks. The safety requirements of Appendix VI of the IAEA Advisory Material have been taken into account. It has been shown that the adopted Eurocode 3, Annex C, method allows an economical calculation of critical failure length on a high level of safety. A failure probability of $p_f = 8 * 10^{-7}$ is reached by applying lower bound estimates of fracture toughness and an additional additive safety factor ΔT_a of 20°C. In comparison to the ASME K_{IR}-reference curve also the strain rate approach of the new concept proved to be on the safe side.

EUROCODE 3; AN EUROPEAN RULE FOR THE DESIGN OF STEEL STRUCTURES

The European market is controlled by directives prepared by the Commission of the European Communities and agreed by the Council of Ministers. For the preparation of technical specifications for products in the construction field the Commission has initiated the preparation of harmonised European Design Standards, the Eurocodes. The Eurocodes are being prepared by CEN TC 250 and first drafted as pre-standard, ENV status, to enable expert discussion and refinement for the final conversion into an EN standard.

Eurocode 3, Part 1, *Design of Steels Structures, General rules for Buildings* has been published as pre-standard for steel structures and buildings in 1992. The method for the choice of steels to avoid brittle fracture has been based on a fracture mechanic safety concept and has initially been published as an informative Annex C to Eurocode 3, Part 1. Until 1997 the Annex C has been worked over under consideration of a newly developed fracture toughness Master-Curve (Wallin, 1990), of a modified Sanz-Correlation (Sedlacek et al., 1993), of the Eurocode 3 fatigue loading detail catalogue and of a quantitative reliability analysis based on safety assumptions that are applied for all design rules of Eurocode 3, (Annex Z,1992). It is now enclosed into Eurocode 3, Part 2, Bridges. The advantages of the new approaches are, that the defined limit state of failure can be quantified by fracture mechanics and that no experimental fracture mechanic toughness data are needed, because the charpy transition temperature and the strength as indicated in material standards are used for the material characterisation by means of correlations and the master curve concept. The procedure has been validated by means of large scale tests.

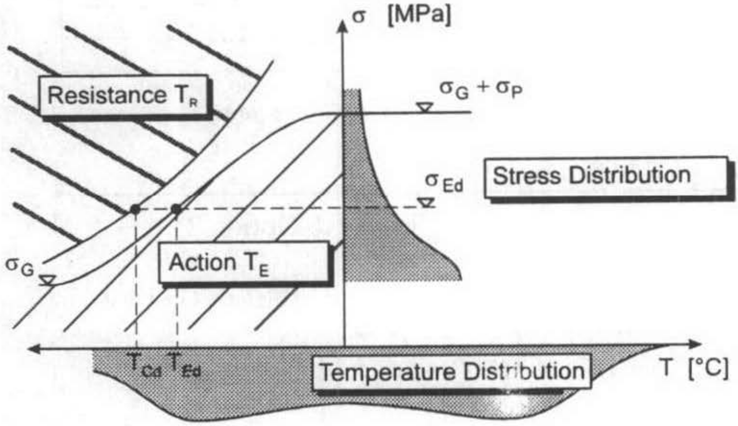
FRACTURE MECHANIC PROCEDURE OF EUROCODE 3, PART 2, ANNEX C

The fracture behaviour of steel components that might bear crack-like defects from fabrication and operation is a function of applied loads and component geometry on the loading side and material toughness and strength on the resistance side. Figure 1 illustrates schematically the temperature dependency of these parameters and thus clearly indicates that with decreasing temperature the risk of brittle failure increases due to an exponential loss of toughness. To take account of the temperature dependence of all parameters the limit condition in Annex C is formulated in temperatures. In its simplest form it may be expressed as follows:

$$\textit{Design temperature } T_{Ed} \geq \textit{Resistance temperature } T_{Cd} \qquad (1)$$

The temperature action T_{Ed} depends on the climatic conditions and consists of two elements as described in Figure 1. The temperature resistance T_{Cd} is mainly dependent on the material toughness, the applied stresses in combination with the assumed crack geometry and the component geometry as well as the loading rate. Each parameter is calculated as a separate temperature and added to the reference temperature T_{100}. T100 is the temperature, where the material exhibits a fracture toughness of 100 Mpa$\sqrt{}$m and is used for the transition temperature correlation with the charpy transition temperature T_{27J}. The applied fracture toughness of the component represented by a fracture mechanic model (Figure 2) is based on the CEGB-R6-Concept (Harrison et al., 1986). The two criteria failure assessment curve (Option 2) allows the consideration of elastic plastic material behaviour while linear elastic stress intensity factors solutions are applied. The required toughness under limit conditions is then transferred into a temperature shift ΔT_r using the K-master-curve (Wallin, 1990) and added to the basic equation. For example, if K_{mat} equals 100 MPa√m ΔT_f becomes 0 and T_{Cd} equals T_{100}. The strain rate effect ΔT_v in the brittle to transition regime can be described by the temperature shift of the Master Curve and is derived empirically as a function of the material strength and the strain rate applied (Falk, 1993). Finally, a partial safety factor ΔT_a is added, which has been derived from a semiprobabilistical evaluation of large scale tests that failed brittle by applying Annex Z of Eurocode 3 (Stranghöner et al., 1997).

A more detailed description of Annex C is provided in a Background Documentation (Sedlacek et al., 1997).



$$T_{Ed} \geq T_{Cd}$$

$$T_{Ed} = T_{min} + \Delta T_{\gamma A}$$

- Low Air Temperature in Combination mit σ_{Ed}

$$T_{min} \approx -25°C$$

- Radiation Effect

$$\Delta T_r \approx -5°C$$

$$T_{Cd} = T_{100} + \Delta T_f + \Delta T_v + \Delta T_{\gamma c}$$

- Influence of Material Properties

$$T_{100} = T_{27J} - 18\ [°C] \qquad (1)$$

- Effect of the applied stesses and fracture mechanic model

$$\Delta T_f = 52 \cdot \ln\left[\frac{(K_{mat} - 20) \cdot K_t - 10}{70}\right]\ [°C] \qquad (2)$$

- Strain Rate Effect

$$\Delta T_v = \frac{1440 - f_y(t)}{550} \cdot \left(\ln \frac{v}{v_0}\right)^{1,5}\ [°C] \qquad (3)$$

- Partial Safety Factor after Annex Z

$$\Delta T_a = -7°C\ (\text{für } \beta = 3,8) \qquad (4)$$

Figure 1: Design concept of Eurocode 3, Annex C

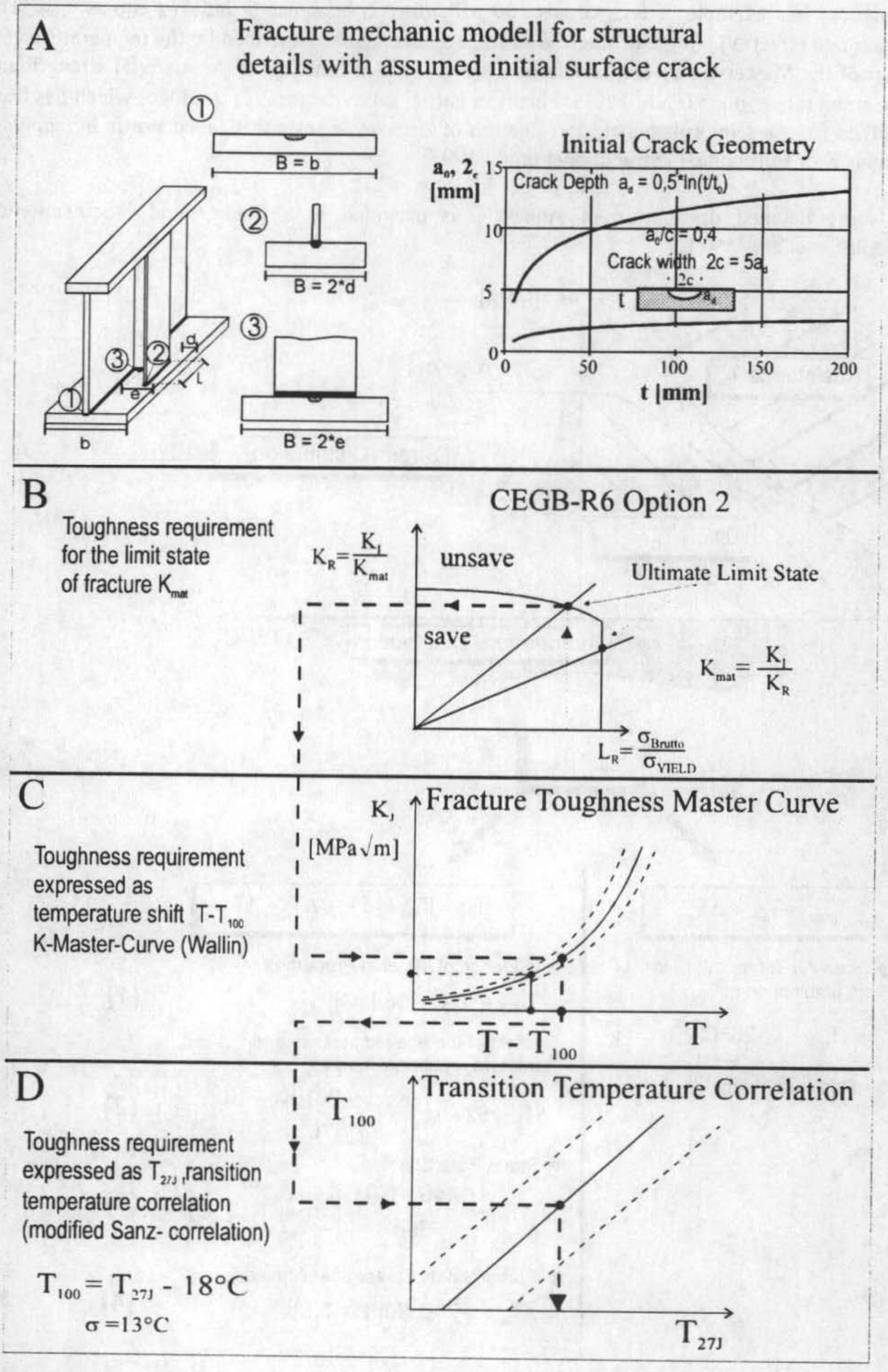


Figure 2: Fracture mechanic model of Annex C

APPLICATION OF THE ANNEX C PROCEDURE OF THE ANNEX C PROCEDURE FOR LIDES MADE FROM FERRITIC LOW ALLOY STEELS

The safety against brittle fracture of lids for nuclear transportation casks when accidental high impact loading is applied has to be guaranteed down to a service temperature T_{Ed} of -40°C. To derive this safety the IAEA design rules for material selection recommend the application of a fracture mechanic safety approach (Appendix VI). Method 3 in this code gives advice on a fracture mechanic approach in terms of linear elastic fracture mechanic solutions. For elastic plastic materials it is indicated to consider elastic-plastic corrections that may either be taken from the CEGB R6 method or the British Standard BSPD6493. For the sake of minimising the risk of failure under accidental conditions due to model deviations and material scatter **it is recomended to apply an overall safety factor** of 1,4 to the fracture toughness as well as **selecting** lower bound toughness and upper bound loading values.

Forged lids made of fine grained ferritic steels today yield **very** good toughness **levels**. In order to achieve practical and economical safety assessment procedure for such lids Annex C was chosen and had to be adopted to the requirements of the IAEA-Appendix VI.

The target value to be assessed is the critical crack geometry which has to be related to the minimum percebtible crack size by means of NDT. The boundary conditions for the safety analysis are as follows:

Required material toughness:	$T_{27J} = -40°C$
Lowest design temperature:	$T_{Ed} = -40°C$
Design stress level:	$\sigma_P = 0.7$ * yield strength f_y (t), $f_y(t) = f_{y,nominell'} - 0,25 * t/t_0$ (t_0 = 1mm)
Design residual stress:	$\sigma_S = 100$ MPa
Maximum strain rate:	$\nu = 0,1\ s^{-1}$
Failure aspect ratio a/c:	a/2c = 1 : 6
Plate thickness:	t = 200 - 600 mm

The applied stress and strain rate values correspond to the design stress level and the dynamic loading observed in 9 m drop test of casks, (Dreier et al., 1995). Secondary stresses have been taken over from the Annex C assumptions. Required temperatures and the failure aspect ratio are given by the IAEA, Appendix VI and the plate thickness results from the design of the cask safety system. The fracture mechanic model is a surface crack in a plane plate (Newman and Raju, 1981) under tensile loading, which, due to the fact that pure bending is expected, is a conservative assumption.

The calculation of the target value, the critical crack length $a_{crit.}$ is only possible by iteration. To simplify this for practical and qiuck design decisions some simplifications have been made which are conservative up to a given crack depth of 12 mm and for plate thickness between 200 and 600 mm:

- The stress intensity correction factor Y of the Newman Raju solution has been taken constant as 1,12,
- The component flow stress is set equal to the yield strength.

SAFETY ASSUMPTIONS FOR THE APPLICATION OF THE TRANSFERRED ANNEX C PROCEDURE

The safety concept of the Eurocodes is related to limit states of design such as serviceability, ultimate and fatigue limit state. Herein, the ultimate limit state is comparable with the accidental requirements of the IAEA document. It corresponds with collapse or other forms of structural failure which may endanger the safety of people. The Eurocodes distinguish between actions S and resistances R. In order to avoid failure of a structure, the design value of the action has to be equal or smaller than the design value of the resistance. Due to the fact of scattering effects both on the action side S and the resistance side R, partial safety factors have to be considered on both sides in the balance of the ultimate limit state.

The derivation of such partial safety factors is based on material and component tests and ruled in Eurocode 3, Annex Z, 1992. The failure probability for standard failure consequences is chosen to $p_f = 7 * 10^{-5}$ which corresponds to a so called safety index $\beta = 3{,}8$. The safety index β is the distance between the mean value of a model function and the failure probability expressed as β times the standard deviation σ.

In case of the Annex C procedure a population of 19 large scale tests has been taken for the derivation of the partial safety factor ΔT_a. In contrast to the normally used multiplicative safety factor γ the Annex C safety factor is additive because the limit state is described in a temperature format and each equation contributes additively to the reference temperature T_{100}. In standard steel design only nominal values as specified in standards are taken for design. The statistical procedure of Annex Z therefore takes account of nominal values by comparing the calculation of failure temperatures on the basis of the measured plate properties under consideration of the model scatter expressed in mean deviation plus β (given failure probability) times the standard deviation with those calculated based on nominal values. The result for the population of 19 tests is $\Delta T_a = -7°C$. This positive result is due to the much better steel quality of the tests in relation to the nominal values. In case that the mean value of a material population is very near to the nominal value, the partial safety factor becomes positive.

For the adoption of Annex C to lids of nuclear transportation casks, the safety recommendations of the IAEA document have been applied as follows. Three inidividual equations (1) to (3) as described in Figure 1 contribute to the calculation of T_{Cd}. Instead of using mean value functions of equations (1) and (2), lower bound estimates for a failure probability $p_f = 0{,}05$ has been used to calculate the change of the original Annex C partial safety factor ΔT_a. From the Annex Z calculation taking on the basis of a test population of 19 large scale tests a new ΔT_a of +20°C has been derived, which corresponds to an overall failure probability of $8 * 10^{-7}$ or a safety index ß of 4,8. Equation (3) that covers the strain rate effect on fracture toughness has not been changed due to the fact that the approximation of the empirical formulae is a lower bound estimation of experimental fracture toughness data at high loading rates and that no statistical evaluation of scatter was available at the time beeing.

In spite of that, a confirmation of the conservatism of this approach, especially at high loading rates, has been worked out by comparing it with the ASME code, Appendix G, 1983, „Protection against nonductile failure". ASME provides a K_{IR} - reference curve which is similar to the Wallin Master curve and attributed as a lower bound estimate of *static, dynamic and crack arrest critical K_I values measured as a function of temperature on specimens of 533 Grade B Class 1 and SA-508-1, -2 and -3 steel*. This curve is normalised by the RT_{NDT} temperature which is not available for the steels treated here. Therefore RT_{NDT} temperatures had to be related to the material toughness specification by using equations (1) and (2) to calculate K_{mat} equal to $T_{27J} = -40°C$ and than from the ASME K_{IR} reference curve finally RTNDT. The calculation of K_{mat} was carried out for the failure probabilities $p_f = 0{,}05$ and $p_f = 0{,}01$. The results of the calculation of the critical crack depth a_{crit} and crack length $2c_{crit}$ are given in the following table for the two fine grain steels with nominal yield strength of 355 MPa (TSte355) and 460 MPa (TSte460):

Steel Grade (t = 600 mm $\sigma = \sigma_p + \sigma_s$ σ_p =0,7 yield strength σ_s = 100MPa)	**Annex C** **adoption** with $\Delta T_a = +20$ K equivalent to pf = 0,05	**ASME** **Section III** **Appendix G** material input values for $p_f = 0,05$	**ASME** **Section III** **Appendix G** material input values for $p_f = 0,01$
TSte355	a = 8,4 / 2c = 50,2	a = 9,1 / 2c = 54,6	a = 4,5 / 2c = 26,9
TSte 460	a = 5,9 / 2c = 35,4	a = 5,4 / 2c = 32,3	a = 2,7; / 2c = 15,9

Table 1: Critical crack depth a_{crit} and crack length $2c_{crit}$ in mm

This comparison clearly indicates that even if a 1% lower bound estimate for the calculation of the RTNDT temperature of the ASME K_{IR} reference curve is used, the adopted Annex C with a partial safety element of ΔT_a of +20°C equivalent to the 5 % lower bound estimates of the calculation formulae of T_{Cd} yields a comparable failure assessment.

The partial safety factor ΔT_a seems to be temperature dependend if one calculates it down to a level of K_{mat} between 20 and 50 MPa√m. Figure 3 demonstrates the effect of the exponential relation between K and $T-T_{100}$. The scatter of K_{mat} in the left picture and of the theoretical (temperatures can not directly be tested) scatter of $T - T_{100}$ in the right picture results from the comparison of the $p_f = 0,5$ with the $p_f = 0,01$ failure probability curves. It is known from experiments that scatter of K in the low range runs into small values. But it can be stated as physically not meaningful that the difference between the curves in terms of temperatures increases to infinity. Therfore, the partial safety factor expressed as a temperature has to be applied as constant also in the lower K_{mat} range below 50 MPa√m.

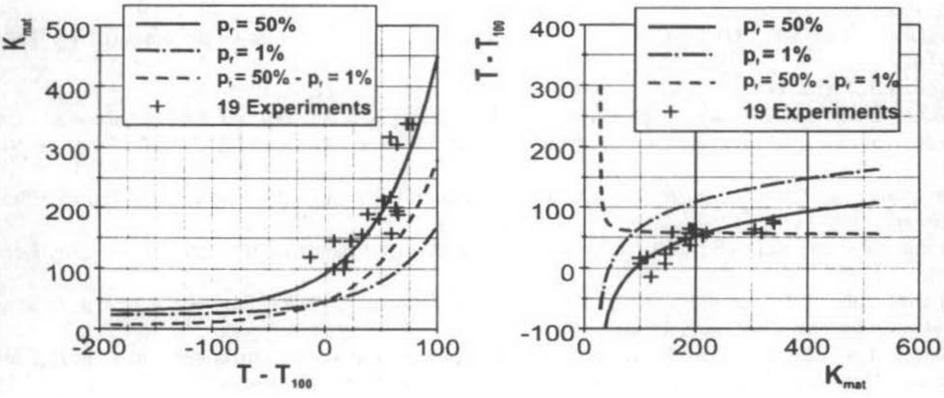


Figure 3: **Fracture toughness master curve, difference between mean value, 50% - and 1%-fractile curve and experimental values of 19 large scale tests with ferritic steels (f_y = 355 - 960 MPa)**

DISCUSSION AND CONCLUSIONS

The conditions for which safety of lids of casks has to be,guaranteed are defined in the IAEA design rules. Maximum loads and loading rates are well known from results of several component tests and simulations of the 9 m accidental drop of a cask. The application of a fracture mechanic safety approach is recommended in Appendix VI and a safety factor of 1,4 is recommended in addition to lower bound toughness and upper bound loading. The Annex C procedure is based on well established fracture mechanic methods and allows economical design based on nominal values from material standards. The safety of the model is derived on the basis of large scale tests applying a semiprobabilistic method and a failure probability of $p_f = 7 * 10^{-5}$.

The adoption of the Eurocode 3, Annex C procedure for lids under consideration of the IAEA recommendations yields to a failure probability of $p_f = 8 * 10^{-7}$. This high level of safety has been compared to the ASME recommendations. It is confirmed to be safe-sided. The question of temperature dependend partial safety factors can be answered negative from the physics behind the applied models.

Finally, the decision of taking over this safety concept for ferritic steels lids is no more a matter of the reliability of the concept itself but of the decision of the competent authorities on the risk level to be tolerated.

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