Comparison of the Elastic and Elastoplastic Approaches for Brittle Fracture Assessment

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INTRODUCTION

In general, TRANSNUCLEAIRE uses a dedicated forged carbon steel (SA 350 grade LF 5) to manufacture the body of large casks for spent fuel transport. Thick-walled bodies ensure the main biological protection and the confinement of radioactive materials. For transport safety as required by the Intenational Atomic Energy Agency Regulations (IAEA 1990, Safety Series no. 6) for type B packagings, the steel confinement should provide sufficient structural resistance during drop tests, including at low temperature (-40°C), which implies the justification of the absence of brittle fracture.

Risk of brittle fracture in this carbon steel is mainly related to the presence of initial flaws similar to cracks, to the stress intensity during impacts, and to the low temperature. To reduce this risk, preventive measures during design and manufacturing have to be taken.

During manufacturing, an ultrasonic examination is performed to detect flaws with a minimum size of 6 mm (1/4 inch). The body is rejected if such flaws are detected. Then, to prove that flaws of equal or smaller size are acceptable from the brittle fracture point of view, specific studies using a Finite Element method are achieved, taking into account cracks of 6 mm length.

The demonstration involves three steps :
drop tests on a scale model in order to determine the maximum decelerations recorded during the most detrimental drop. These deceleration values are then used as multiplication factors for the static loadings;
a tridimensional calculation approach in order to assess the stress situation during these drops; and
a bidimensional equivalent approach in order to assess the risk of crack propagation in the areas of maximum tensile stress.

The aim of this paper is, through the treatment of a recent case related to the " TN 24D " cask, to describe a general method based on fracture mechanics, which can be used to assess the risk of brittle fracture and is suitable for both linear elasticity and elastoplasticity. This method is also compared with a method based on the calculation of the stress intensity factor K_I, which is normally restricted to the linear case.

PRESENTATION OF THE STUDIED CASK

The cask in this study is intended for the transport and for the intermediate storage of 28 spent fuel assemblies PWR 17 x 17. The TN 24D cask is mainly a thick carbon steel shell, closed on the bottom side by a bulk welded flange and closed on the top side by two bolted covers, as shown in Figure 1.

DROP CONFIGURATION

The risk of brittle fracture may occur during accident conditions at low ambient temperature (-40°C), when the ovalization or the bending of the structure induces tensile stresses. That means that tensile stresses tend to open longitudinal or annular cracks included in the cask body. These effects happen especially during horizontal drops on the shock absorbers or on the trunnions. The last case involves the highest tensile stresses, which are found around the trunnions area. As regards the risk of brittle fracture, it is the most harmful case. The cases of oblique and vertical drops for this cask have been eliminated because the compression stresses in the cask axis are important and the tensile stresses are much lower than previously.

STRESSES STATE

Maximum tensile stresses in the cask occurring in the horizontal drop on trunnions are calculated with a static formulation of a tridimensional model, taking into account the maximum deceleration values measured on a third-scale model during the drop tests.

This model includes the shell and its bottom, and the primary and secondary lids. The loading takes into account the weights of secondary structures (basket, fuel, shock absorbers, cask neutron shielding, and outer structures). Conditions on displacements are significant for the gap between the body and the lids, the incompressibility of the lids (bulk steel plates), the cask symmetry, and the contact with the unyielding target.

As input for the static calculation, the peak deceleration value of 200g measured in horizontal drop test on trunnions (the most severe case) is used.

In this situation, an ovalization of the shell typically is observed until the gap between the body and the lids is reduced to zero. At this point, at the top of the cask, the lids are incompressible as bulk steel plates and they resist to the shell deformation. The ovalization induces a local plastic deformation on the upper part of the free edge of the cylinder interacting with the lids. Another plastic deformation zone ($\sigma > Sy = 320$ MPa at -40°C) appears close to the junction of the trunnions to the shell.

SOLVING THE 3D PROBLEM IN ELASTICITY

The stresses are evaluated through this tridimensional mesh (see Figure 2) with a purely elastic calculation, which overestimates the stresses since these overpass the yield strength locally in areas of highest stresses. In fact, by taking into account the material elastoplastic deformation law, a redistribution and general diminution of the stresses would occur.

The study is then focused on the tensile stresses, which can open the longitudinal (σx) or annular (σz) cracks. As regards risk of brittle fracture, the most stressed area is located closed to the free edge near the trunnion base, on the internal surface of the shell (see Figure 3), where the both terms of tensile stresses are maximum.

REDUCTION OF THE 3D PROBLEM TO THE 2D PROBLEM IN ELASTO-PLASTICITY

A tridimensional elastoplastic problem in fracture mechanics for a structure with cracks is difficult to study in its integrality. However, crack modeling in elastoplasticity can be reduced to the simplified bidimensional problem using the superposition principle in first assessment of the tensile stresses. The tendency for propagation of cracks is then evaluated by the method of J-integral calculation, which is applicable both in linear and nonlinear fields.

In fact, for a solid with a crack, the stresses state in the solid without the crack can first be determined in the 3D problem. Then, the calculated stresses are applied on the crack lips in a 2D formulation, for which the resolution is equivalent to the resolution of the direct problem of a solid with a crack, according to the superposition principle.

In fact, the superposition principle is perfectly applicable in the linear field, which means in the case of a problem around a crack, if the plastic area at crack extremity is small compared to the crack length.

The use of the superposition principle can be criticized in case of larger plastic deformations. However, as shown in this paper, its use is also valid for the resolution of the present problem. In a first step, the use of the superposition principle, which combines rigorously with a linear resolution of the 2D problem with crack, will provide a first evaluation of the stress intensity factor K_I and of J-integral value assuming linear conditions (see Figure 4). These first results must be looked upon with caution, since the influence of plasticity is not taken into account. Then, in a second step, the elastoplastic deformation law of the material is taken into account, in a new resolution of the 2D problem with crack. This calculation aims to provide an evaluation of the change of J-integral value under plastic influence, to compare the results of elastic and nonelastic calculations, and, finally, to assess the consistency of the whole methodology.

SOLVING THE 2D PROBLEM IN LINEAR FIELD AND IN ELASTOPLASTICITY

In accordance with the bidimensional problem formulation, a 6 mm length crack is modelled in the most critical area near the top trunnion. The tensile and bending stresses, which have been found in the tridimensional problem resolution, are applied on the crack lips at a certain distance for a better accuracy of the calculation.

The same process is applied both for the initial linear resolution and for further nonlinear resolution. In this latter case, the elastoplastic behaviour law is introduced with the hardening parameters of the material. In general, the boundary conditions translate the crack position on the symmetry axis, the crack extremity as a fixed point, and the material continuity on both parts of the cracks.

RETAINED CALCULATION METHODS OF K_I AND J

This paper does not detail the classical formulations of the different expressions of the applied stress intensity factor K_I and of the J-integral calculation. The criteria are :
in elasticity :

$$K_I \leq K_{Ic} \quad \Leftrightarrow \quad J \leq J_c$$

where $K_I^2 = \dfrac{JE}{1-\nu^2}$

J_c : critical J-integral

K_{Ic} : toughness of the material.

in elastoplasticity :

$$J \leq J_c$$

In order to compare with the results of elastic calculations, it is still considered that the concept of stress intensity factor K_I is in some extent valid in elastoplastic field, through the approximate relation : $K_I^2 = \dfrac{JE}{1-\nu^2}$; As an acceptance criteria, the recalculated, K_I value can still be compared to material toughness K_{Ic}.

FRACTURE MECHANICS SOLUTIONS FOR LINEAR ELASTICITY

For the forged carbon steel of the body, the material toughness K_{Ic} is 170 MPa $\sqrt{m}$. The applied stress intensity factor K_I for two cases is solved by resolution of the elastic problem in the bidimensional formulation, using the two methods indicated below :

1- Drop on trunnions, longitudinal crack (σx)

2- Drop on trunnions, annular crack (σz)

Calculated case	K_I (Benthem) (MPa . $\sqrt{m}$)	K_I, EDI (MPa . $\sqrt{m}$)	K_I / K_{Ic}
1	34,2	34,3	0,20
2	66,1	66,5	0,39

K_I calculation with simplified method found in the work of Benthem :

$$K_I = (1{,}1215.p + 0{,}439.q).\sqrt{(\pi a)}$$

where a : length of the crack

p : load on the bottom crack extremity (p_{max} = 418,8 MPa in case 2)

q : such load that (q+p) is the load on top crack extremity (q_{max} = 27,5 MPa in case 2)

EDI : K_I calculation with the Equivalent Displacement Integration (EDI) method through the J-integral calculation.

The comparison of the results obtained by the simplified method and of the calculated ones by the Finite Element method using the EDI method shows good agreement. The analysis of the ratios K_I / K_{Ic} indicates that the calculated cases are safe as regards risk of brittle fracture, as far as linear fracture mechanics is applicable.

FRACTURE MECHANICS SOLUTIONS FOR ELASTOPLASTICITY

The resolution of the elastoplastic problem is shown on Figure 5. The analysis of the plastic area dimensions for the load 2 shows that the plastic zone extremity is well developed (14,5 mm) and overpasses the crack length. This is why the linear mechanics results, as calculated previously, are not totally reliable, and why it is necessary to calculate J-integral value taking into account the elastoplastic material deformations.

Figure 6 shows the stresses σy distribution, evaluated with the elastoplastic calculations, perpendicular to the crack line. The zone disturbed by the presence of the reduced dimension crack is small compared to the total calculation area.

The J-integral is calculated by a specific module in the computer code using the following formulation :

$$J_k = \int_{\Gamma_\varepsilon} (w.n_k - \sigma_{ij}.\frac{\delta U_i}{\delta x_k} n_j).d\Gamma \text{ J}$$

where σ_{ij} : stress
U_i : displacement
Γ_ε : small path around the crack extremity
n_j : component of the path normal

The K_I and J-integral are calculated in both cases.

Calculated case	J (MPa . m)	J / Je	$K_I = \sqrt{\frac{JE}{1-\nu^2}}$ (MPa . √m)	K_I / K_{Ic}
1	0,00521	1,14	36,7	0,22
2	0,02190	1,28	75,2	0,44

The value of the ratio J/Je represents the plastic influence. Je is the J-integral value in elasticity, J in elastoplasticity.

For case 1, the calculation of the ratio K_I / K_{Ic} though the J-integral value leads to very similar result as in linear mechanics. This is because the stresses around the studied crack stay below the plastic deformation threshold.

A modification appears in the ratio K_I / K_{Ic} for case 2, which leads to a diminution of the safety as regards risk of brittle fracture. This is due to the spread plasticity area around the crack (see Figure 7). However, in terms of K_I values, the difference between the two approaches does not exceed 13 %.

CONCLUSION

In the frame of this study, the two methods of assessment used provide similar results and lead to the conclusion that the package remains safe during impacts at low temperature as regards risk of brittle fracture. In the studied case, tensile stresses overpass locally the yield strength and, in spite of that, the elastic approach of rupture mechanics would have been sufficient to assess risk of brittle fracture, regardless the safety margin (K_I versus K_{Ic}) compared to the influence of elastoplasticity. Nevertheless, this study should be completed by solving other cases to confirm the field of validity of the linear approach.

According to the results, one of the main conclusions is that if the packaging design offers reasonable safety margins, it should be possible to validate the results of the linear analysis (K_I) within elastoplastic deformation areas.

REFERENCES :

François D., Malesys P. Cask resistance study as regards the brittle fracture (Safety Analysis Report TN-0845-Z-1-5-6, Rev. 0 of 93.11.16.)

Benthem J.P., Koiter W.T. Asymptotic approximations to crack problems. IN : Mechanics of Fracture, v.l Methods of Analysis and Solutions of Crack Problems. Leyden: Noordhoff Int. Publ., 131-178 (1972).

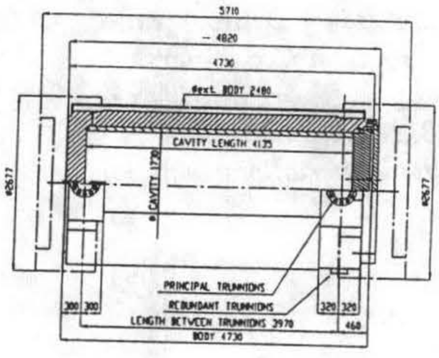


Figure 1

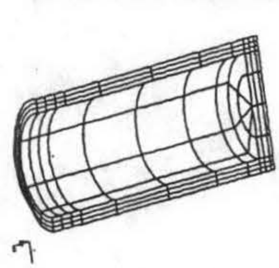
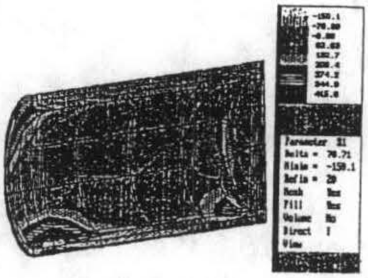


Figure 2



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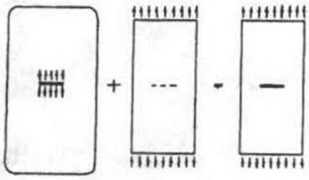

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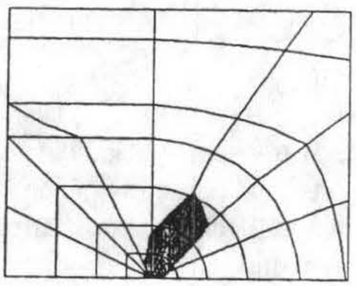

Figure 5

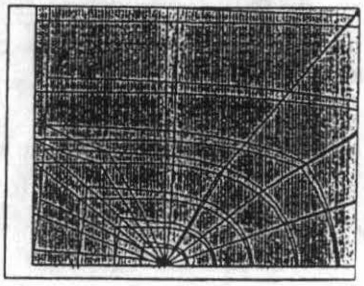

Figure 7

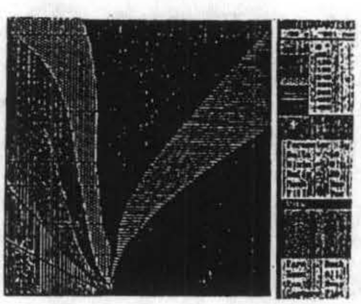

Figure 6

Figure 1 : Sketch of the TN 24 D cask

Figure 2 : Mesh for the 3D finite element model

Figure 3 : Stresses state during horizontal drop on trunnions

Figure 4 : Principle of superposition in linear fracture mechanics

Figure 5 : Plastic area at the crack extremity

Figure 6 : Stresses state (σy) perpendicular to the line of the crack

Figure 7: Deformation on the crack extremity