Brittle Fracture in Transport Casks: Evaluation of Methods to Predict Crack Initiation

T. Yuritzinn, D. Moulin, S. Foglia, M. Bourdette
Commissariat à l'Energie Atomique

J.Y. Reculeau
Institut de Protection et de Sûreté Nucléaire

INTRODUCTION

For the acceptance of the B(U) packages for the transport of radioactive material, the manufacturers must demonstrate their integrity for the transport of these materials. The containers must be able to sustain the most severe drop conditions recommended by the IAEA at an ambient temperature of -40°C. This requirement implies that the absence of a risk of a sudden fracture is justified, especially for thick cast iron or forged ferritic steel containers. Recommendations concerning an elastic-plastic treatment of the risks of brittle fracture, i.e., taking plasticity into account in the K_I and J criteria are discussed in order to be introduced in the draft Appendix IX of IAEA Safety Guides No. 37.

To assess the applicability and the validity of different evaluation methods for the risk of fracture, the Institut de Protection et de Sûreté Nucléaire (IPSN) has undertaken, with the support of the CEA/DRN/DMT mechanical engineering laboratories, a research and development program on this subject.This R&D program, which aimed to improve our knowledge of the mechanical behavior of a container, has now been completed. The approach adopted in this program was to carry out tests on container mock-ups and cracked rings, together with numerical simulations of tests with CASTEM-2000 finite-element codes for the static case and PLEXUS code for the dynamic case. These codes were developped at the CEA, using an elastic-plastic behavior model based on the mechanical characteristics of the material in order to establish a simplified method for J calculation.The objective is to determine the J value at the time corresponding to the initiation of the crack and to compare this value with the toughness of the material, the most significant mechanical property in this behavior.

This presentation describes some of the developments made in France to check the validity of methods proposed to evaluate the risk of brittle fracture and in particular the proposals of the IAEA draft of Appendix IX based on nonlinear plastic fracture mechanics relying on J.

This method for determining the value of J corresponding to crack development requires the presence of a flaw. It is then necessary to machine a notch in the specimen so as to localize the damage to be avoided, i.e., initiation and development of a crack.

The material was characterized at three different strain rates ($\dot{\varepsilon} = 0{,}11\%.s^{-1}$, $55\%.s^{-1}$, $500\%.s^{-1}$) at room temperature. Tests were also undertaken to determine the static and dynamic toughness of the material.

DYNAMIC TEST WITH CONTAINER MOCK-UP

The container mock-up is made of a SA 350 LF1 ferritic steel. The mock-up considers the container body without shock absorbers, cover, or components. The instrumented test was carried out at CEA/CESTA and its aim was a drop with the mock-up cylindrical axis horizontal, from 9 m onto a rigid target.

To ensure initiation and development of the crack, a longitudinal notch was machined on the open side of the mock-up (the other end being closed). The notch was machined on the inside diameter of the cylinder over half the thickness of the ring. It was noted that the predominant deformation mechanism was the ovalization of the mock-up on the open-ended side, which explains the crack development observed at the end of the test.

A 3D numerical simulation of the test was conducted with the PLEXUS fast dynamics code. Good agreement was obtained between the experimental data and the numerical results. The difference between the experimental measurement and numerical prediction of the vertical displacement of the accelerometer A1 was less than 10%.

As the code PLEXUS is not dedicated to the determination of J values, a 3D calculation with CASTEM-2000 code was made. The gravity was increased until the vertical ovalization of the open side of the container mock-up was identical to the maximum value obtained in the dynamic simulation. The mesh close to the notch was designed with concentric circles centered on the crack front in order to respect the specifications required for using the G-Theta procedure implemented in CASTEM-2000 for determining J. It was assumed that the CASTEM-2000 computation gives the mock-up behavior for a constant crack length. On the curve showing the J parameter versus vertical ovalization for the two extremities of the crack, the comparison with the static toughness allows us to predict that initiation of the crack has occurred for a vertical ovalization of 9 mm for the open-end of the mock-up (section A). This value was necessarily reached since the maximum ovalization observed during the test was 14 mm. Because we have only an estimation of the dynamic toughness, the comparison with this value is not presented.

STATIC TEST WITH A CRACKED RING

Based on the result showing that the ovalization of the open-end of the mock-up is the predominant deformation mechanism, it is possible to use a much simpler configuration, representative of the bare mock-up; it consists of a 2D approach of the mock-up as a cracked ring subjected to a vertical ovalization.

The static test has consisted of a compressive crushing of the cracked ring (A.F. specimen). The principle of the test is shown schematically together with its instrumentation. The aim of the test was to induce initiation and development of the crack.

The machined notch extends over the entire width of the ring with a depth equal to half the ring's thickness. It is terminated by a 60° angle with a radius of the notch base of less than 0.1 mm. Due to symmetry, the mesh was reduced to half the width of the cracked ring. To facilitate the modeling, the machined notch geometry was simplified by a line with double nodes. The mesh close to the notch was designed with concentric circles centered on the crack front in order to conform to the specifications required for using the G-Theta procedure implemented in CASTEM-2000 for determining J.

The variation of the force applied on the ring as a function of the vertical ovalization is compared for the edge and the center of the ring with the experimental data. The 3D behavior of the ring is revealed by the non-superposition of the curves obtained at the ring center and at the edge. A good agreement between the test and the numerical results is obtained for values of vertical ovalization up to approximately 25 mm, the last value for which the difference between the actual force and the numerical value is below 10 %. This result is confirmed by the variation of the ovalization versus strain recorded for the strain gauge J1, which presents a deviation for an ovalization of 23.5 mm. We have assumed that this deviation corresponds to the initiation point of the crack.

It can be observed that for the same compression force, the J value is greater at the center (point F) than at the edge (point A) of the ring. This means that the toughness of the material is first reached at the ring center. A crack initiation visible on the side of the ring is thus subsequent to that produced at the center of the ring. In the test, the crack initiation was estimated visually for a compression of 57 mm measured on the edge of the ring. However initiation at the center of the ring occurs for an ovalization of 23.5 mm.

The value of J (900 kJ/m^2) corresponding to a compression of 23.5 mm is approximately equivalent to the static toughness of the material (890 kJ/m^2), as can be observed in the distribution of J versus vertical ovalization shown for the ring center.

DYNAMIC TEST WITH CRACKED RING

In this test, a weight has been dropped on a A.F. (Anneau Fissuré = Cracked Ring) specimen so as to initiate cracking and subsequent cracking. A schematic representation of the dynamic test used in CEA/CESTA is shown with the experimental arrangement and instrumentation. Tridimensional numerical simulations of this dynamic test were made with the PLEXUS fast dynamics code. The falling weight has an initial velocity of $\sqrt{2gh}$ where h is the drop height. The contact between the ring and the supporting block is made with blocked vertical displacement for the ring points that can be in contact with the supporting block. As carried out here, the modeling is only valid for the first impact of the block on the ring. It cannot simulate the detachment of the ring from the centering component.

There is very good agreement between the dynamic test results and the computational results at the time corresponding to the maximum value, with a deviation of less than 2% for the vertical ovalization at the center of the ring.

Similar to the dynamic test with the container mock-up, a 3D calculation with CASTEM-2000 code was made. The applied force was increased until the vertical ovalization at the center of the ring was equal to the maximum value obtained with the dynamic simulation. The mesh used for this simulation is identical to the one used for the simulation of the static test made with the cracked ring.

At the end of the test, a flaw of less than 0.1 mm was observed at the bottom of the notch corresponding to initiation of cracking in the center of the ring. It was assumed that crack initiation was produced at the time coinciding with the maximum ovalization of the ring. It corresponds to a value of 16.4 mm at the ring center. The value of the extent of the restitution of the energy J for the dynamic initiation is 730 kJ/m^2. On the curve showing the distribution of J versus vertical ovalization, the value of J corresponding to a drop of 5 m (which has resulted in a maximum vertical ovalization of 18.5 mm and a cracking of about 1 mm) is also presented. Comparison of these values with the static touhgness of the material shows a good agreement, less than 4% for the 5-m experiment.

CONCLUSION

A method has been presented to determine the initiation of a crack using the J criterion, the J value being calculated using PLEXUS and CASTEM-2000 finite element codes. It can be seen that the static computation is valid only if the ovalization is properly determined. Our next step in this study will be the application of our method to an actual cracked container. We will also focus our attention on having a consistent method for determining the dynamic toughness.

VALIDATION OF SIMPLIFIED METHOD TO EVALUATE CRACK INITIATION
DYNAMIC TEST
DROPPING OF A WEIGHT ON A CRACKED RING - ANALYTICAL CASE

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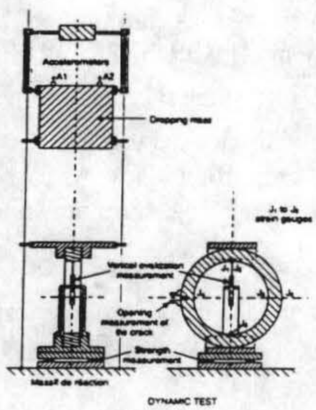
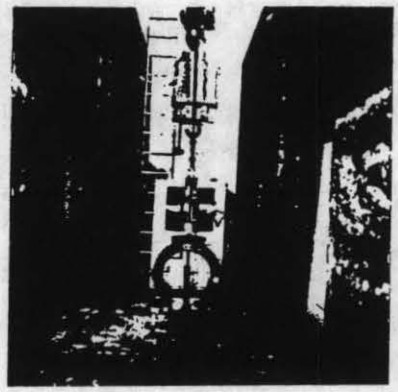
PRINCIPLE OF THE TEST - DETAILED INSTRUMENTATION



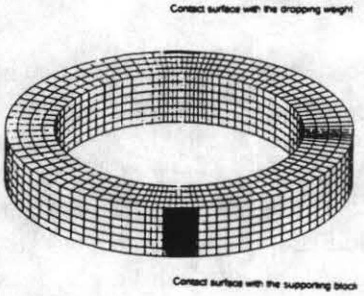
DYNAMIC TEST



SIMULATION WITH PLEXUS CODE

3D MESH FOR THE DYNAMIC SIMULATIONS

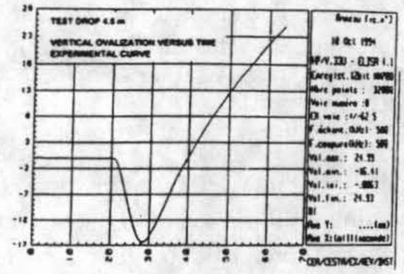
Contact surface with the dropping weight

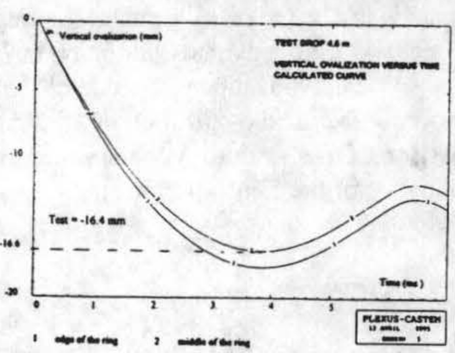


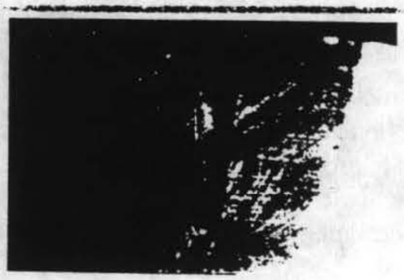
Contact surface with the supporting block

MESH 3444 nodes (14 double nodes)
2352 8-element nodes

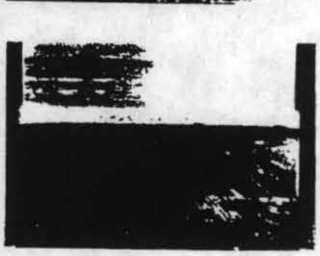
machined crack (half the ring's thickness)
simplified with a line of double nodes

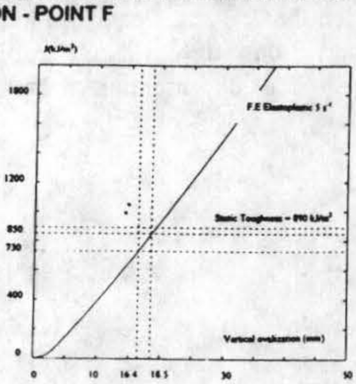






ESTIMATION OF J PARAMETER WITH CASTEM 2000 CODE
IMPOSED OVALIZATION - POINT F





J VERSUS OVALIZATION
COMPARISON WITH THE STATIC TOUGHNESS

height of test drop	maximum ovalization	propagation of the machined crack
4.5 m	16.4 mm	< 0.1 mm
5 m	18.5 mm	≈ 1 mm

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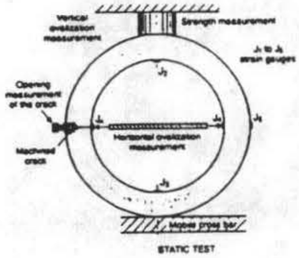
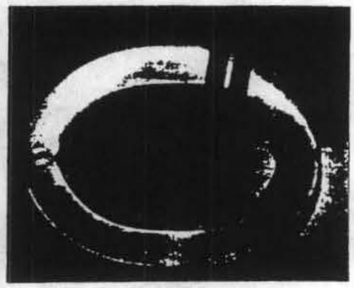
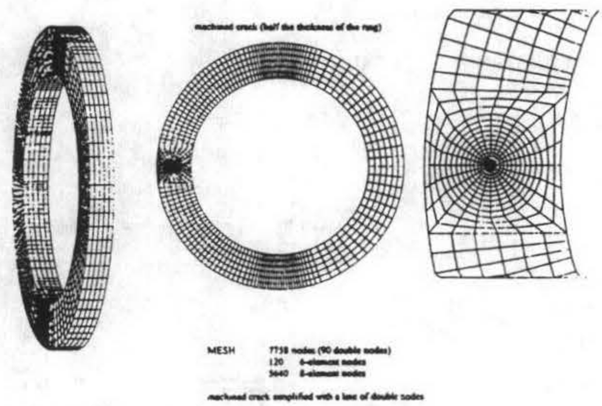
VALIDATION OF SIMPLIFIED METHOD TO EVALUATE CRACK INITIATION
STATIC TEST
A COMPRESSIVE CRUSHING OF A CRACKED RING - ANALYTICAL CASE

PRINCIPLE OF THE TEST - DETAILED INSTRUMENTATION

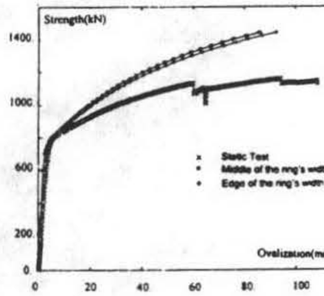




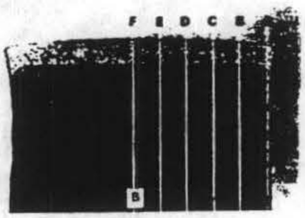
SIMULATION WITH CASTEM 2000 CODE - INITIAL CRACK



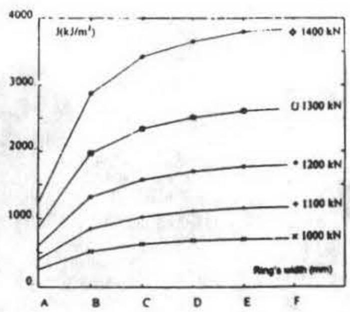
FORCE VERSUS OVALIZATION



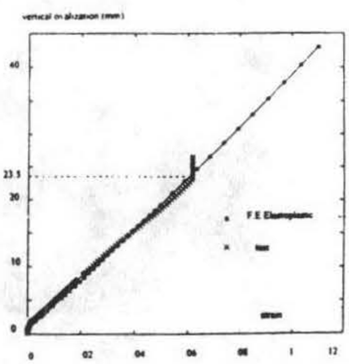
CRACK FRONT



LOCAL J THROUGH WIDTH

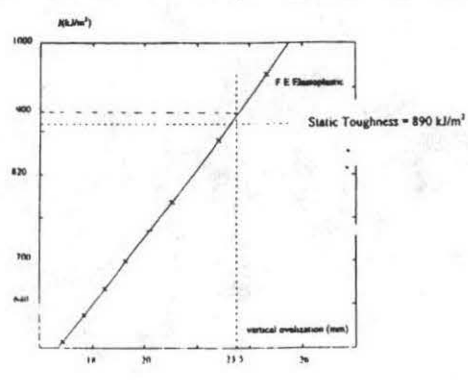


OVALIZATION VERSUS STRAIN



J AT POINT F VERSUS OVALIZATION
COMPARISON WITH THE STATIC TOUGHNESS

VALIDATION OF THE METHOD



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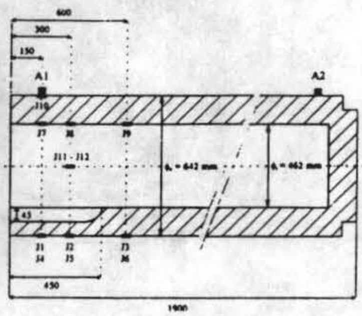
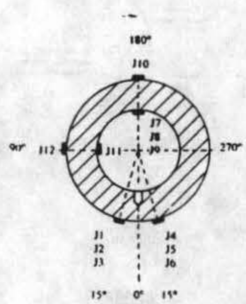
VALIDATION OF SIMPLIFIED METHOD TO EVALUATE CRACK INITIATION

DYNAMIC TEST

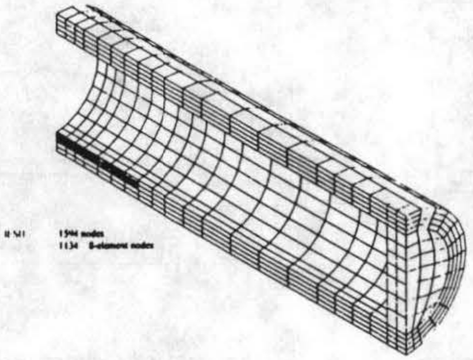
DROP OF THE HEIGHT OF 9 m OF A CONTAINER MOCK- UP WITHOUT SHOCK ABSORBERS, COVER OR COMPONENTS

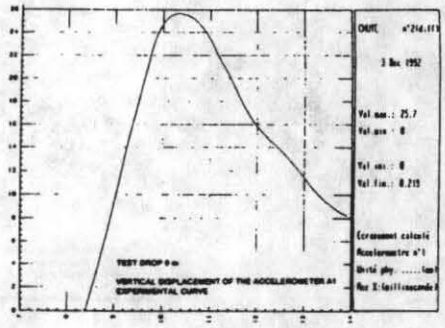
MACHINED INITIAL CRACK - DEPTH = 45 mm (half the thickness of the mock-up)

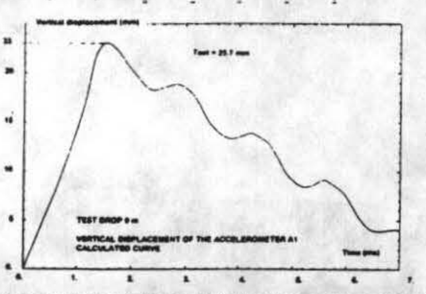


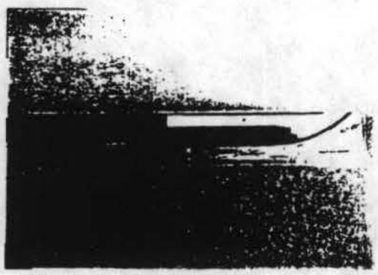


SIMULATION WITH PLEXUS CODE





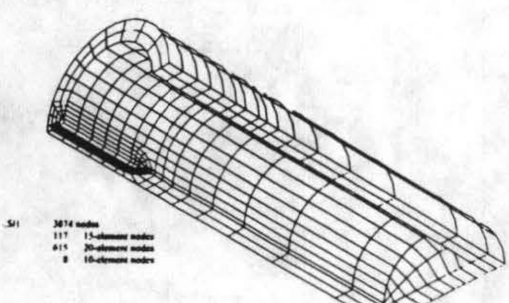


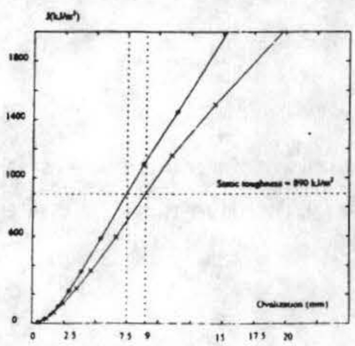


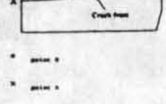
MAXIMUM PROPAGATION = 25 mm at point A
MAXIMUM OVALIZATION = 14 mm at point A

ESTIMATION OF J PARAMETER WITH CASTEM 2000 CODE IMPOSED OVALIZATION -

J VERSUS OVALIZATION
EQUIVALENT GRAVITY
COMPARISON WITH THE STATIC TOUGHNESS







Session VII-1: Industrial/Type-A Package Development