VALIDATION OF A FRACTURE MECHANICS APPROACH TO NUCLEAR TRANSPORTATION CASK DESIGN THROUGH A DROP TEST PROGRAM

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ABSTRACT

Sandia National Laboratories (SNL), under contract to the Department of Energy, is conducting a research program to develop and validate a fracture mechanics approach to cask design. A series of drop tests of a transportation cask is planned for the summer of 1986 as the method for benchmarking and, thereby, validating the fracture mechanics approach. This paper will present the drop test plan and background leading to the development of the test plan including structural analyses, material characterization, and nondestructive evaluation (NDE) techniques necessary for defining the test plan properly.

BACKGROUND

There is considerable interest in the cask community to manufacture transportation cask bodies from materials other than stainless steel. In the United States licensing concerns for such candidate materials (i.e., nodular cast iron and ferritic steel) focus on the fact that such materials exhibit a ductile/brittle failure mode transition. Hence, casks made from these candidate materials may be subject to brittle fracture under certain loading and environmental conditions.

A fracture mechanics approach to cask design will provide the ability to predict material response for a particular cask design subjected to external loadings. This approach is suitable to designs using a ductile/brittle material which may have fatigue flaws or material defects present. A conservative initial approach to modeling crack behavior is linear-elastic fracture mechanics (lefm). The approach is conservative because no account is taken for the zone of plasticity at the crack tip. The fundamental lefm equation which predicts crack initiation is:

$$K_{Ic} = C\sigma\sqrt{\pi a_c} \qquad (1)$$

Where K_{Ic} = Critical stress intensity factor (Fracture toughness parameter), MPa $-\sqrt{m}$
C = Constant = f (crack geometry, location, and orientation of the crack in the structure)
σ = Maximum nominal tensile stress (MPa)
a_c = Critical crack depth (m)

According to Eq. (1) failure due to brittle fracture can be prevented by limiting any flaw size or material discontinuity below the computed value of "a_c," for a specific cask material and design, given K_{Ic} and σ.

K_{Ic} is a material property that is dependent on material microstructure, strain rate, and temperature. The application of Eq. (1), therefore, is based on the specific cask parameters: material, design, and loading. Variation of any of these parameters will affect the fracture toughness value, the applied stress, and, hence, the computed critical crack depth.

The purpose of this drop test program will be to monitor crack behavior in a cask subjected to external loading. Actual crack behavior will then be compared with predicted crack behavior. The prediction of crack behavior will validate the fracture mechanics methodology as applied to cask design. In addition, NDE procedures will be evaluated in terms of sensitivity and reliability. Results of the NDE investigation should provide a basis for recommending specific NDE procedures for cask inspections.

The test methodology, as described in this paper, is divided into the following phases:

1. Predrop structural analyses
2. Material characterization testing
3. Inspection techniques

Gesellschaft fur Nuklear Service (GNS), a cask developer from West Germany, has donated two MOSAIK casks to Sandia. The casks are made out of nodular cast iron which exhibits a ductile/brittle failure mode transition. This makes the casks ideal for applying the fracture mechanics methodology. The MOSAIK I, Fig. 1, is lead lined and will be used primarily for material characterization testing. The

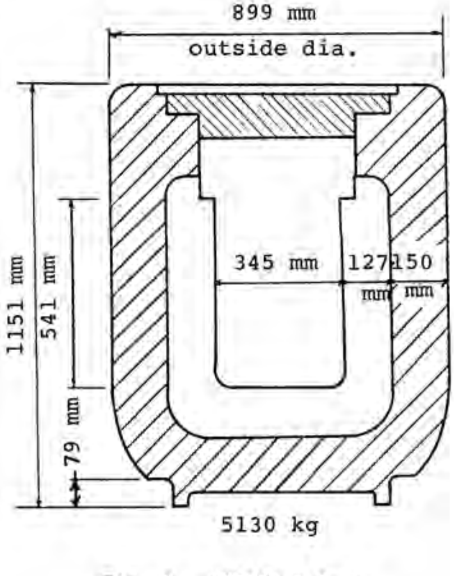


Fig. 1. MOSAIK I Cask.

MOSAIK KfK, Fig. 2, is not lead lined and will be used as the test specimen for validating the fracture mechanics approach and for benchmarking the modeling techniques and codes used.

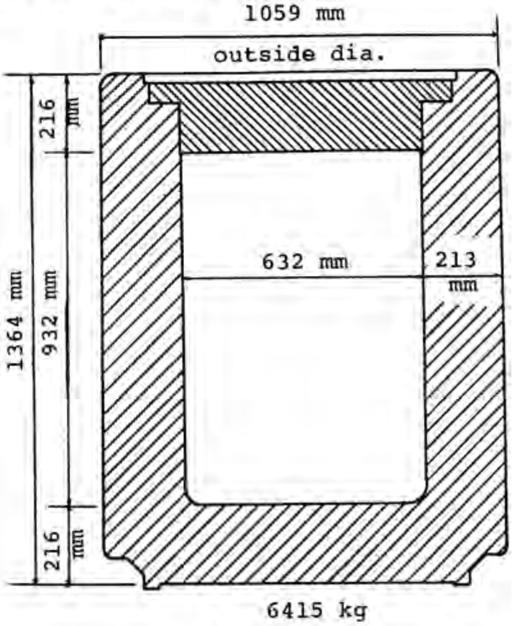


Fig. 2. MOSAIK KfK Cask.

Predrop Structural Analyses

The predrop structural analyses serves two purposes. First, they will be used to verify the modeling techniques and codes used for determining material response to drop events of the type specified in the "Code of Federal Regulations," Title 10, Part 71[1].

Secondly, the analyses were performed to determine the drop orientation which would produce stresses conducive to crack propagation. The "best" stress environment for promoting crack extension is a through wall tensile stress with a mild stress gradient. A stress distribution which ranges from tensile to compressive is not desirable since crack propagation may be arrested in the compressive zone.

The drop orientation best suited to meet these requirements was determined to be a side drop onto end rail supports; one rail located under each end of the cask. In this orientation the cask acts as a short beam in bending with the lower cask wall developing only tensile stresses.

The best drop height for the tests was determined to be 9 meters based on the stresses produced. Drops less than 9 meters produced stresses significantly less than yield, whereas drops up to 30 meters increased maximum tensile stresses by only 20 percent over the 9-meter drop. This is due to increased plasticity exhibited in the rail supports. Experimental difficulty outweighed the benefit of a marginal increase in stresses in choosing the 9-meter drop height over the 30-meter drop height.

Figure 3 shows the finite element model used for the analyses. Because of symmetry only a quarter of the cask is modeled. The predrop analyses were performed on the MOSAIK KfK only. Fig. 4 shows the elements which experience the highest stresses. Correspondingly, Fig. 5 plots stress-time histories for these elements.

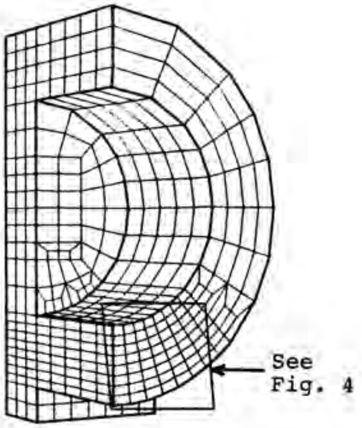


Fig. 3. Finite Element Model of the MOSAIK KfK Cask.

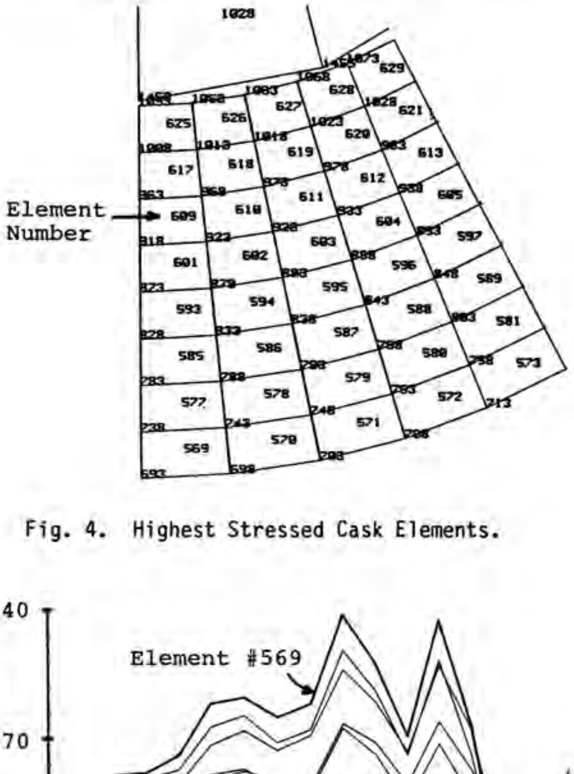


Fig. 4. Highest Stressed Cask Elements.

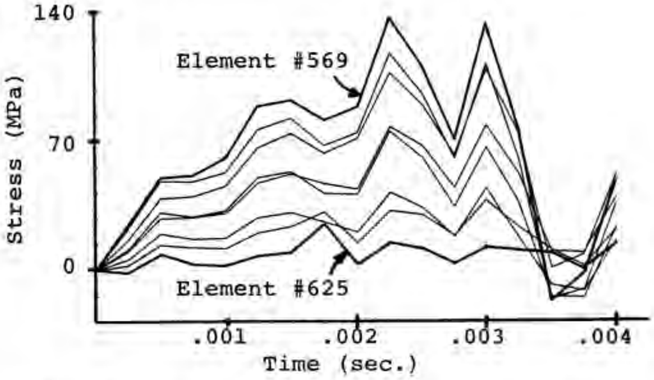


Fig. 5. Stress Histories of Highest Stressed Elements.

The highest stressed element (No. 569, Fig. 4) reaches 140 MPa, which is two-thirds of the 225 MPa yield stress. For monitoring crack behavior, it would be desirable to have the maximum tensile stresses close to yield. Along with varying the drop height, the cask was modeled as having the basket area filled with different materials in an effort to increase the stresses. These analyses resulted in increased stress gradients as well as the introduction of a compressive zone of stress in the area of interest.

For the drop event shown in Fig. 3, 100-mm-thick rail end supports were used. The effects of using different material for the rail and different rail widths were investigated using the finite element method. The optimum target (rail end support) is a 100- by 100-mm carbon steel rail with a yield strength of about 350 MPa.

As a result of the predrop analyses on the MOSAIK KfK, the drop test criteria will stipulate a 9-meter drop height and a side drop orientation onto 100- by 100-mm end supports constructed out of mild steel (350 MPa yield strength). All drops made will meet these criteria.

The first drop will be made with the MOSAIK KfK without any manufactured flaws. The purpose of this test will be to compare experimental data with analytic results using DYNA3D [2], which is an explicit time integration code.

Subsequent to benchmarking of the modeling technique and computer code, a series of drop tests will be performed in order to monitor actual crack behavior which will be compared to fracture mechanics analyses results. The only variable in the drop tests will be crack depth. An initial crack will be subcritical in size. The cask will be dropped and then inspected for evidence of crack growth. Subsequent drops will have increasingly larger cracks manufactured into the cask wall. This process will continue until the cask fails, as evidenced by crack propagation through the cask wall.

Solving Eq. (1) for the critical crack depth, a_c, yields:

$$a_c = \frac{1}{\pi}\left\{\frac{K_{Ic}}{\sigma C}\right\}^2 \qquad (2)$$

The manufactured flaw will be planar and machined into the outside wall of the cask. The crack plane will lie normal to the cask axis and, therefore, will be normal to the applied tensile stress. Figure 6 shows the orientation and geometry of the crack with respect to the applied stress.

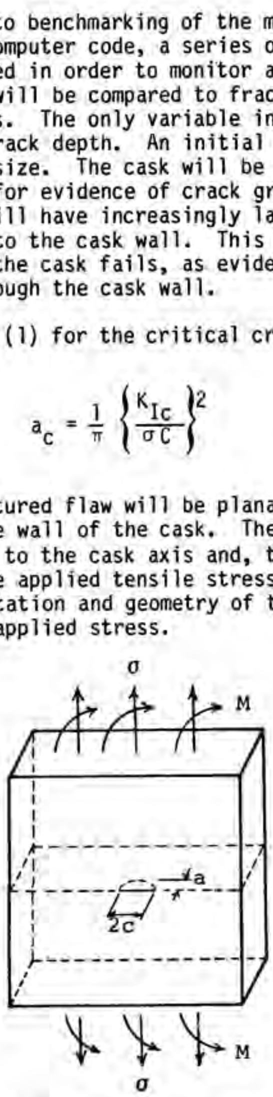


Fig. 6. Part-Through Thumbnail Crack.

For a surface crack with an orientation as shown in Fig. 6, handbook values for the constant, "C," can be obtained. However, Eq. (2) assumes a constant stress distribution, σ, across the cask wall. This is not the case for the MOSAIK KfK drop test as shown in Fig. 5. The stress, σ, varies from 140 MPa to 0 MPa from the outer wall to the inner wall, respectively.

To account for the stress variation, superposition is used; and the stress field is split into a uniform axial stress (70 MPa) plus a linear bending stress distribution (+70 MPa to -70 MPa). The effect of each stress distribution on fracture toughness is individually computed and then added together to determine the total relationship. G. P. Cherepanov describes the procedure in "Mechanics of Brittle Fracture" [3].

For the specific case just described, Eq. (2) can be written in the form,

$$a_c = 0.21\left\{\frac{K_{Ic}}{\sigma^*}\right\}^2 \qquad (3)$$

Where σ^* = maximum axial or bending stress (70 MPa for this case)

The crack will be machined into the cask using the electrical discharge machining method. The smallest crack tip radius which can be achieved is approximately 0.1 mm, which is considered a blunt flaw (not conservative). The crack depth computed in Eq. (3) assumes a sharp flaw. Experimentally it is not feasible to fatigue a sharp flaw into the cask.

The actual effect that a blunt flaw has on Eq. (3) cannot be determined analytically. This effect will be investigated during the actual drop test. In M. W. Schwartz's report "Recommendations for Ductile and Brittle Failure Design Criteria for Ductile Cast Iron Spent Fuel Shipping Containers" [4]; it states that material qualification using a blunt crack testing approach is acceptable with certain qualifications. The blunt crack tip radius must be less than 0.005 times the crack depth, and the crack depth for the production cask is 1/6 the allowable crack depth calculated from Eq. (3).

Materials Testing

Test coupons will be taken from the MOSAIK I to determine microstructure variability across the cask wall and to perform material property tests. MOSAIK KfK properties will be assumed to be the same as the MOSAIK I material properties. Postdrop material evaluations will be made on the KfK to verify this assumption.

Because of the severe geometry restrictions placed on a K_{Ic} test specimen for this material (due to its high toughness) by ASTM E399 [5], a J-Integral test at the drop test strain rate will be performed according to ASTM E813.

The J-Integral value is an elastic-plastic fracture toughness parameter which is correlated to K_{Jd} (K_{Ic} at a drop test strain rate) using:

$$K_{Jd} = \left\{EJ\right\}^{1/2} \qquad (4)$$

Where E = Young's Modulus (MPa)
J = Elastic-plastic fracture toughness parameter (MN/m)

K_{Ic} in Eq. (3) is then replaced by K_{Jd} designating a K_{Ic} value determined by the J-Integral test at the specific drop test strain rate.

The thick-walled nature of the cask and inherent microstructure variation through-section may result in a relatively significant change in the fracture toughness across the wall thickness. Since K_{Ic} is a function of micro-structure, the effect of microstructure variation must be accounted for in the determination of the critical crack size.

M. Schwartz [4] recommends using the following equation for computing the final critical flaw size for a test cask:

$$a_c = a_T \left\{ \frac{K_{Jd}\ (\text{Min})}{K_{Jd}\ (\text{Flaw})} \right\}^2 \qquad (5)$$

Where

a_c = Critical size for test flaw (m)
a_T = Critical flaw size determined from Eq. (3) (m)
$K_{Jd}(\text{Min})$ = Minimum measured fracture toughness value (MPa $-\sqrt{m}$)
$K_{Jd}(\text{Flaw})$ = Measured fracture toughness at the initial flaw location (MPa $-\sqrt{m}$)

Therefore, a complete mapping of the fracture toughness of the material must be made across the cask wall at the location of the manufactured flaw.

As an example, a critical flaw size can be approximated using fracture toughness values from specimens tested from similar material. GNS has donated nodular cast iron material to SNL for testing as part of a parallel research program. A low fracture toughness value for the material is 60 MPa $-\sqrt{m}$ [6]. Using a maximum tensile stress of 70 MPa and Eq. (3), the critical flaw size is geven by:

$$a_c = 0.21 \left\{ \frac{K_{Jd}}{\sigma^*} \right\}^2 \qquad (6)$$

$$= 0.21 \left\{ \frac{60}{70} \right\}^2$$

$$= 0.15 \text{ m}$$

$$= 150 \text{ mm}$$

This value assumes that the ratio $\left\{ \frac{K_{Jd}\ (\text{Min})}{K_{Jd}\ (\text{Flaw})} \right\}$ in Eq. (5) is equal to one.

The cask wall for the KfK cask is 213 mm thick. A 150-mm-deep crack represents a crack-to-wall thickness ratio of 0.70. This is a rather significant crack. It may be that the remaining wall ligament length (63 mm) will not maintain sufficient constraint to ensure linear-elastic plane strain conditions as required in the lefm approach.

Since the initial flaw will be subcritical in size (<<150 mm), the lefm approach should be adequate in modeling material response for the first few drops. However, as the flaw size increases; the amount of constraint the structure exhibits decreases to the point that the linear-elastic plane strain assumption becomes overly conservative.

This condition is evidenced during the experiment by stable crack growth (ductile tearing). At this point in the experiment, an elastic-plastic fracture mechanics (epfm) approach must be used to properly model material response. The J-Integral method of computing fracture toughness will be used coupled with a nonlinear finite element analysis. The epfm approach accounts for the large zone of plasticity present at the head of the crack tip and, therefore, provides a more accurate model.

<u>Inspection Techniques</u>

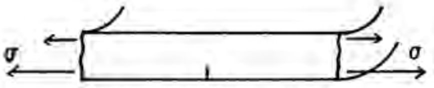
Nondestructive testing efforts will focus on providing:

i) An initial mapping of the cask to inspect for material discontinuities and
ii) a method of nondestructively examining the cask postdrop for determining if crack extension has occurred.

For both efforts the MOSAIK I will be used to qualify a recommended NDE procedure. An inherent problem of the nodular cast iron is the relatively high attenuation characteristics. For thick wall specimens the attenuation factor can become significant. For this cask it is anticipated that a frequency as low as 1 MHz will have to be used for ultrasonic inspection.

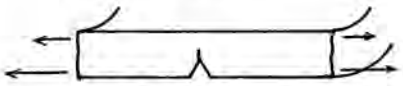
In examining for crack extension, ultrasonic testing (UT) will be used. At the crack tip the wave becomes diffracted. The level of diffraction and, hence, crack tip extension can be measured. This procedure will be qualified on MOSAIK I material prior to drop testing the KfK cask.

Schwartz [4] recommends that crack extension greater than 3.2 mm (≈10 mils) constitutes failure. The NDE procedure used should be able to detect crack extension of at least 3.2 mm. In the event an NDE procedure cannot be qualified for detecting crack extension, a destructive method will be used. Figures 7a, b, and c illustrate the procedure. A crack is machined into the cask wall (Fig. 7a). After each drop a V-shaped test coupon will be machined out of the wall. The test coupon will enclose the crack (Fig. 7b). The test coupon will then be examined for crack extension. A new crack will then be machined into the apex of the notch for a subsequent drop test (Fig. 7c). This procedure can continue in an iterative fashion until large-scale crack extension occurs.



a. Manufactured flaw

b. Test coupon



c. Extended manufactured flaw

Fig. 7. Crack Inspection Technique.

CONCLUSION

The calculation of the critical crack depth by Eq. (3) will provide a lower bound factor of safety to brittle fracture. The calculation of a_c states that crack extension may occur for a crack depth larger than a_c.

For a reasonably tough material (such as nodular cast iron), the calculation of critical crack depth by Eq. (3) becomes suspect if the initial crack depth becomes large relative to cask wall thickness. The nominal tensile stress, σ, is computed as if the flaw did not exist and as if the material acts in a linear-elastic fashion. As the flaw becomes larger relative to wall thickness, these assumptions become invalid. The plane strain requirements placed on K_{Jd} become invalid as the net section thickness decreases. Hence, linear-elastic fracture mechanics becomes overly conservative. No credit is taken for the large zone of plasticity at the crack tip.

This condition will be monitored during the test. As the crack depth increases, nonlinear analysis, coupled with a J-Integral fracture toughness determination, will be used to model actual crack behavior and material response.

Initial crack extension at a crack depth higher than the computed (lefm) critical crack depth does not constitute failure of the fracture mechanics approach. It does provide a quantifiable bound on the factor of safety for this specific cask material and design. Crack initiation at a crack depth smaller than that computed by Eq. (3) would give rise to concern.

The results of the test should show that although an lefm approach to cask design may not be entirely accurate, it will err on the conservative side. It can, thus, become a viable design approach to qualifying the candidate material for cask construction.

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