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CASK CRUSH PAD ANALYSIS USING DETAILED AND SIMPLIFIED ANALYSIS METHODS[1]

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INTRODUCTION

A crush pad has been designed and analyzed to absorb the kinetic energy of a hypothetically dropped spent nuclear fuel shipping cask into a 44-ft. deep cask unloading pool (Fig. 1) at the Fluorinel and Storage Facility (FAST). This facility, located at the Idaho Chemical Processing Plant (ICPP) at the Idaho National Engineering and Environmental Laboratory (INEEL), is an U. S. Department of Energy site. The basis for this study is an analysis by Uldrich and Hawkes (Ref. 1).

The purpose of this analysis was to evaluate various hypothetical cask drop orientations to ensure that the crush pad design was adequate and the cask deceleration at impact was less than 100 g. It is demonstrated herein that a large spent fuel shipping cask, when dropped onto a foam crush pad, can be analyzed by either hand methods or by sophisticated dynamic finite element analysis using computer codes such as ABAQUS (Ref. 2). Results from the two methods are compared to evaluate accuracy of the simplified hand analysis approach.

ANALYTICAL PROCEDURE

The hand analysis technique developed by Miller (Ref. 3) was used to perform the one-dimensional hand analyses. This technique was adapted into the computer program Mathcad 6.0 (Ref. 4). Using Mathcad allowed analysis of many different drop orientations with both a loaded and unloaded cask, by changing only a few pertinent parameters. The Miller technique requires setting the potential energy of the dropped cask equal to the strain energy in the foam crush pad. This is an iterative process, which is facilitated by using a program such as Mathcad.

A three-dimensional dynamic finite element analysis was performed using the ABAQUS/Explicit computer program. In the model developed for this analysis, the cask was treated as a rigid body. The foam crush pad was modeled utilizing the built-in foam model of the ABAQUS Code. Some effort was required to ensure that this representation of the foam accurately represented actual test behavior. Compression in the other two orthogonal directions of foam tends to stiffen the foam in its crushing direction. Therefore, the three-dimensional representation of the foam is stiffer than a one-dimensional representation. The initial conditions of the cask place the cask in imminent contact with the crush pad with a vertical downward velocity equal to the cask impact velocity.

DESCRIPTION OF THE POOL, CASK, AND CRUSH PAD

The cask is transported by an overhead crane at a maximum height of two feet above the concrete deck at FAST. The unloading pool is 44 ft. deep with a water depth of 42.5 ft. The foam crush pad was assumed to be 4.5 ft. thick. Therefore, the cask dropped approximately 3.5 ft. through air and 38 ft. through water.

The cask is the 110-ton Large Cell Cask (LCC). Upper and lower bound weights used in the analysis were 220,000 and 160,000 lbs. respectively. The cask has a tapered body with the diameter varying from 81.5 in. at the bottom to 83.5 in. at the top. Consequently, a cylinder with a nominal body diameter of 82.5 in. was used in the analyses along with a nominal body length of 165.5 in. (Fig. 2). The cask has a top mounted lifting lug, which protrudes 22.25 in. above the body and has a width of about 15 in. The cask also has a 7.5-in. chamfer at the bottom corner. The geometric effects of the lug and the chamfer were neglected in these analyses and the cask was always treated as a rigid body.

The crush pads are constructed of 48-in. of 20 pcf rigid polyurethane foam, a ¼-in. stainless steel (SST) top cover plate, a 1-in. SST bottom plate, ½-in. side plates, and two 2 ½-in. SST ballast plates. The two crush pads are 11 ft.-10 in. wide by 18 ft.-2 in. long. The safety factor against floating is 1.27, which is greater than the allowable of 1.1. A lower bound foam density of about 9.0 pcf would produce a safety factor against floating of 1.1.

FOAM MODEL VERIFICATION

One object of the foam model verification was to verify that the ABAQUS representation of the foam model accurately represented the foam behavior as was tested by the manufacturer. The manufacturer tests the foam by fixing a cube, 1.5 in. on a side, to a wall and then impacting it with a pendulum at various velocities. This dynamic impact data is then translated into uniaxial stress-strain data.

The manufacturer's stress-strain data was used to generate an ABAQUS foam hardening model. The ABAQUS verification model is a cube of foam, 1.5 in. on an edge. This foam is restrained on the bottom and is compressed by a rigid surface on the top (Fig. 3). The displacement of the top surface and the reaction force on the bottom surface

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were calculated and converted to stress and strain. These were compared to the manufacturer's data to verify that the ABAQUS foam hardening model produces appropriate results (Fig. 4). The comparison shows that the results from the ABAQUS foam model compare very closely with the original foam data from the manufacturer.

The crushable foam plasticity model, an integral feature of the ABAQUS/Explicit code, was used to represent the foam. It was developed for the analysis of crushable foams that are typically used for energy absorption. The foam plasticity model is used to represent the ability of the foam to deform volumetrically in compression due to cell wall buckling processes. The model therefore works in terms of volumetric stress and strain. This foam model also accounts for the difference between a foam material's compressive strength and its much smaller tensile capacity resulting from cell wall breakage in tension. It can be used when rate-dependent effects are important, such as in a cask impact situation.

THE SIMPLIFIED ANALYSIS

The one-dimensional hand analysis used the technique developed by Miller (Ref. 3). This technique was programmed on Mathcad 6.0 to facilitate the several cask drop orientations and cask weights. By changing the appropriate parameters, the analysis can quickly be redone for a different load case.

In this analysis technique, the strain energy of the foam is made equal to the potential energy of the cask. The stress-strain curve for the foam as furnished by the manufacturer has strain data up to 80%. Over this range, the stress-strain curve is not linear. Also, the volume of the depression in the foam, for most drop orientations, does not increase linearly with the depth. Consequently, the strain energy calculation is an iterative process involving fairly small foam displacement increments. The strain energy is the sum of the energy density increments times the volume increments. The energy density is the area under the stress-strain curve for that particular increment or it is the amount of energy absorbed by each cubic inch of foam.

The potential energy of the cask is basically the weight of the cask times the height of drop. The total drop height is figured from the center of gravity of the cask hanging in the normal vertical position to the center of gravity of the cask in the at-rest position partially imbedded in the foam. The cask does not fall as fast through water as it does through air, so a drop height correction for this is included. The potential and strain energies are made equal by trial and error assumptions of the depth of cask penetration into the foam.

The maximum strain in the foam is the depth of penetration divided by the original thickness of the foam. The average deceleration of the cask is the potential energy of the cask divided by the weight of the cask and the depth of penetration of the cask into the foam. The peak deceleration is the summation of the incremental forces applied to the foam during cask impact divided by the mass of the cask.

THE ABAQUS ANALYSIS

The ABAQUS/Explicit computer code (Ref. 2) was used to perform the dynamic finite element analysis. For the side drop only one-half of the cask was modeled, but all of the mass was included. The cask was modeled as a rigid body. The cask center of gravity was included in cask model. The cask's initial conditions were specified at the center of gravity. A sufficient portion of the crush pad was modeled to eliminate boundary effects. The model of the cask sitting on the crush pad is shown in Figure 5.

The model of the cask in the side drop position is shown in Figure 6. The cask impact velocity used was 619 in./sec. which envelopes the hand analysis velocities of 611 in./sec. for the upper bound cask weight and 597 in./sec. for the lower bound cask weight. The hand analysis impact velocities include the effect of buoyancy in water but neglect the effect of drag. The ¼-inch stainless steel plate that covers the top of the foam in the crush pad was included in this model. In the side drop, this cover plate stretches considerably to conform to the circumference of the cask and probably ruptures near the ends of the cask. The stretching of the plate absorbs significant (about 10% of the total strain energy) strain energy in stopping the cask. The indented crush pad is shown in Figure 7.

A bottom corner impact was also analyzed. That ABAQUS/Explicit computer model is shown in Figure 8. The cask impact velocity used was 594 in./sec. which envelopes the hand analysis velocities of 581 and 568 in./sec. for the upper and lower bound cask weights respectively. The ¼-inch stainless steel plate that covers the top of the foam in the crush pad was not included in this model. In this case the sharp edge of the cask bottom will cause this plate to rupture and bend and therefore, the plate will absorb only a negligible amount of the strain energy. The indented crush pad is shown in Figure 9.

RESULTS

Results for comparison are presented in Table 1. The results for the hand and computer analysis for each case are presented on consecutive lines for ease in comparison. Depth of penetration is tabulated because it is important to insure that the crush pad has an adequate design. The maximum strain in the foam is presented because it is important to limit the foam strain to 60% or less. At 60% the foam cells are about totally collapsed and something equivalent to strain hardening occurs (Fig. 4). The last item listed is the cask deceleration. In many cases, nuclear listed is the cask deceleration. In many cases, nuclear material shipping casks and contents are limited to some maximum deceleration. Up to that deceleration, there is reasonable assurance that the cask will not rupture, thus protecting against spillage of contents or streaming of radiation. In the case of the Large Cell Cask, this deceleration limit was 100 g.

In this report only two drop orientations are reported. All drop orientations were analyzed and were reported in Reference 1. Only two orientations are reported herein because these represent limiting cases. The side drop predicts the maximum cask deceleration from all the possible drop scenarios. The bottom corner drop represents the maximum penetration into the foam. Therefore, it insures an adequate design of the crush pad and sufficiently low straining in the foam.

CONCLUSIONS

Concerning the design of the crush pad, the hand analysis always overestimates the depth of crush. This occurs because the three-dimensional representation of the foam results in a stiffer representation of the foam than in the one-dimensional, hand analysis representation. In terms of cask penetration into the crush pad for the side impact, the hand analysis overestimates the penetration by about 35%. For the bottom corner impact, the hand analysis overestimates the penetration by about 4%. The corner impact has in essence a wedge effect that negates the enhanced stiffness due to the three-dimensional consideration.

Considering the effect of cask deceleration, the three-dimensional computer analysis always produces higher cask decelerations. For the side drop the ABAQUS deceleration is about 13% higher that than predicted by the hand analysis. For the bottom corner drop the ABAQUS deceleration varied from 5 to 12% higher than that predicted by the hand analysis.

The results indicate that it is conservative to design a crush pad by hand analysis methods. However, they indicate that it is somewhat non-conservative to predict cask decelerations by these hand analysis methods. Results obtained from the simplified approach are reasonably accurate. The simplified method is much quicker since it does not require development of a finite element model. The choice of method to use in a particular application depends on level of accuracy required, time constraints, and cost considerations.

REFERENCES

1. Uldrich, E. D. and Hawkes, B. D., "Structural Analysis Support for: Task 20, Crash Shield Analysis; Task 21, Cask Tip-Over Analysis; Task 22, Crush Pad Lifting Analysis; and Task 23, Maximum Lift Height Analysis", EDF Serial Number AMG-08-97, Revision 1, Lockheed Martin Idaho Technologies Company, Inc., Idaho Falls, ID, September 29,1997.
2. Hibbitt, Karlsson, and Sorensen, "ABAQUS/Explicit", Version 5.6, Hibbitt, Karlsson, & Sorensen, Inc., Pawtucket, RI, 1996.
3. G. K. Miller, "Calculation of Impact Loads for High Energy Drops of Cylindrical Containers", International Journal of Impact Engineering, Vol. 13, No. 4, pp. 511-526, Pergamon Press Limited, Great Britain, 1993.
4. "Mathcad 6.0", Standard Edition, MathSoft Inc., Cambridge, MA, 1995.

Table 1. Results for Comparison

Cask Weight	Drop Orientation	Analysis Type	Penetration Deformation	Maximum Strain	Peak Deceleration
220,000 lbs.	Side Drop	Hand	14.7 in.	30.6 %	68.5 g.
		Computer	10.9 in.	22.7 %	78.8 g.
	Bottom Corner	Hand	24.6 in.	51.3 %	37.5 g.
		Computer	23.7 in.	49.5 %	39.3 g.
160,000 lbs.	Side Drop	Hand	12.5 in.	26.0 %	81.8 g.
		Hand with liner	12.0 in.	25.0 %	88.1 g.
		Computer	9.1 in.	19.0 %	97.6 g.
	Bottom Corner	Hand	21.1 in.	44.0 %	42.3 g.
		Computer	20.3 in.	42.3 %	47.9 g.

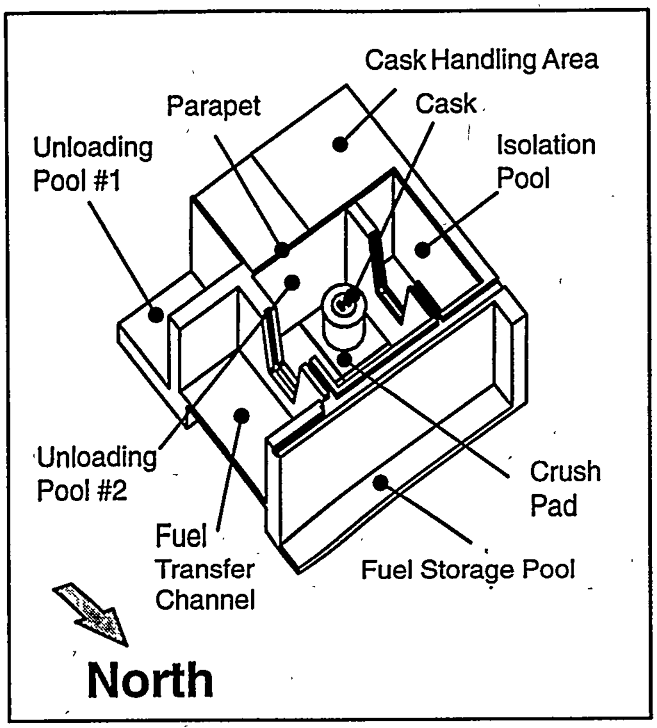

Figure 1. Overall View of the Cask Unloading Pool, the Cask and the Crush Pads

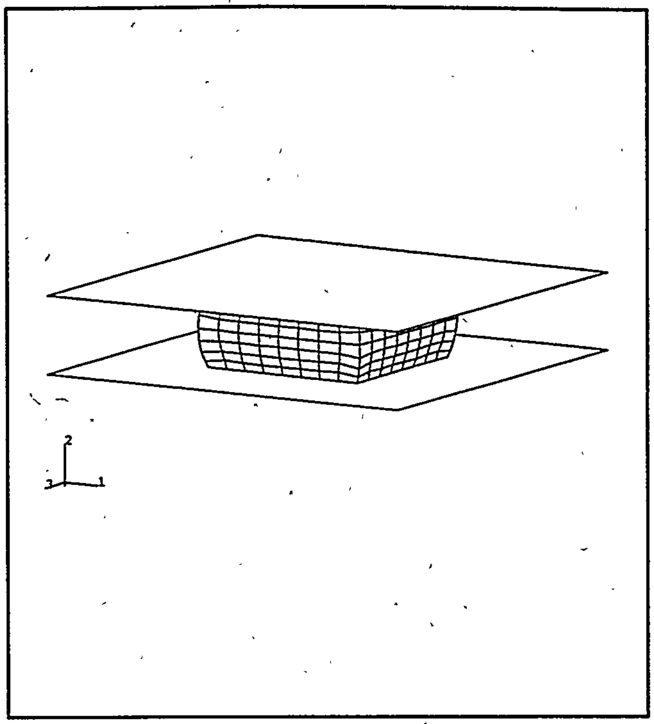

Figure 3. ABAQUS Finite Element Model of Crushed Foam

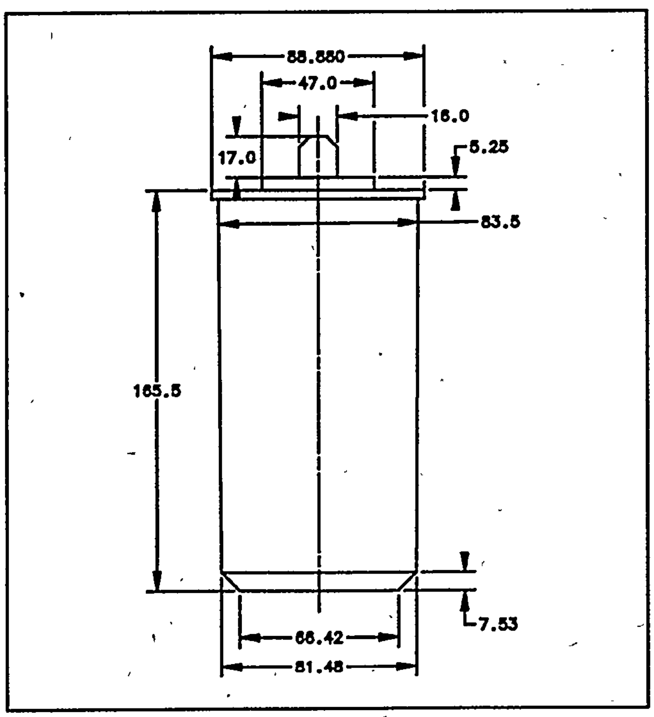

Figure 2. Large Cell Cask Dimensions (in.)

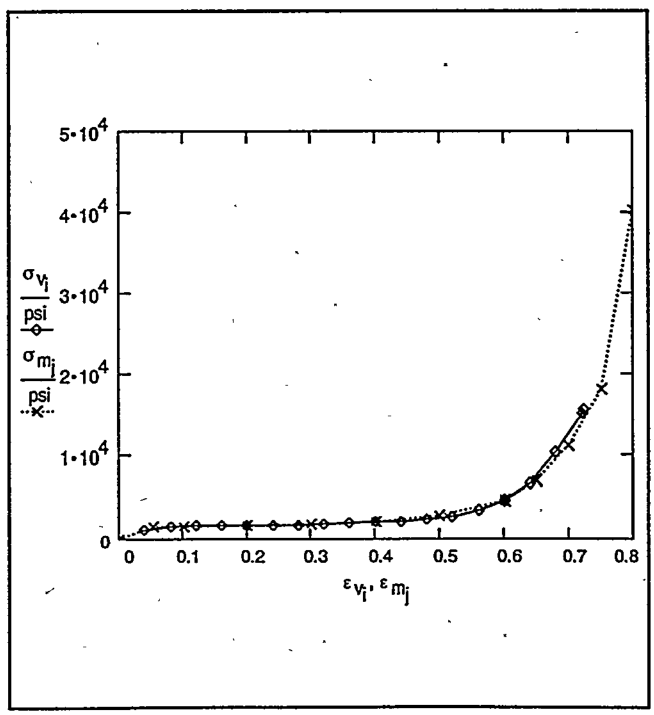

Figure 4. Comparison of the ABAQUS foam model verification (subscript v) results and the manufacturer's (subscript m) test data (σ is stress in psi and ε is strain in in./in.)

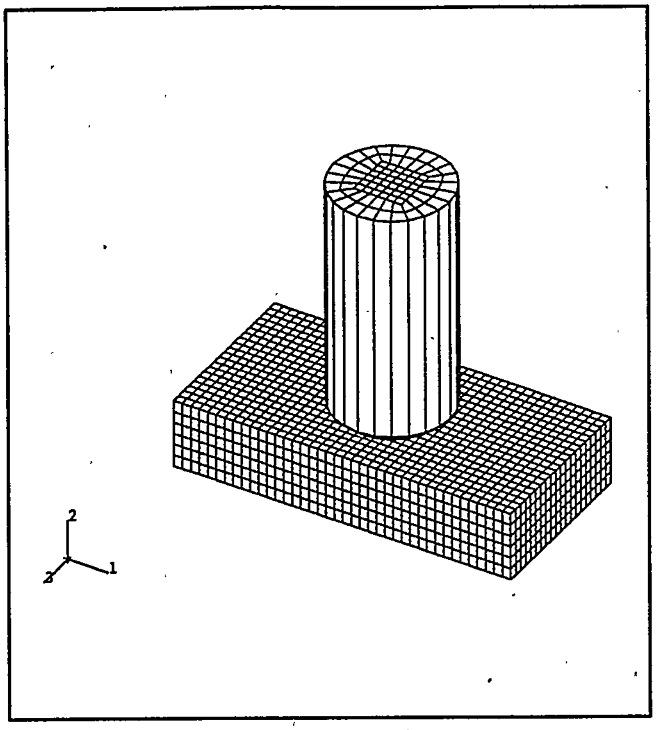

Figure 5. ABAQUS Finite Element Model Showing the Cask and Crush Pad

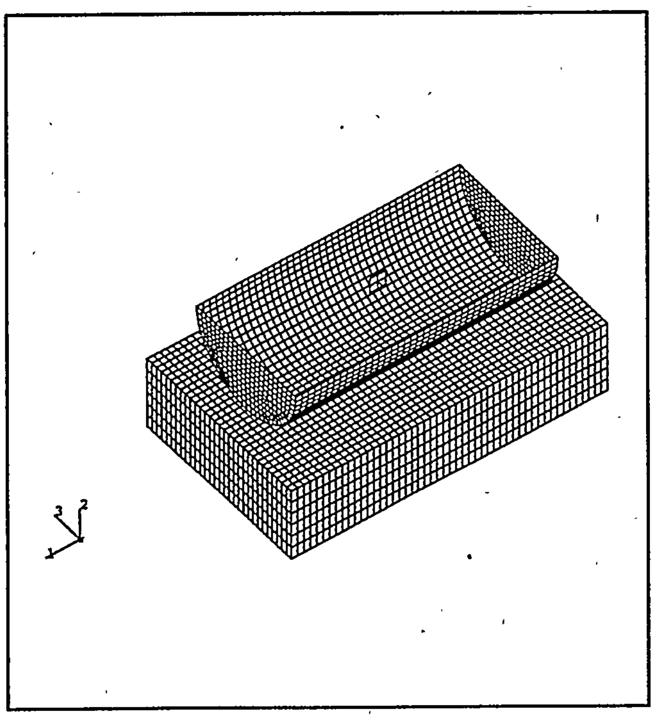

Figure 6. Finite Element Model of Cask Side Drop

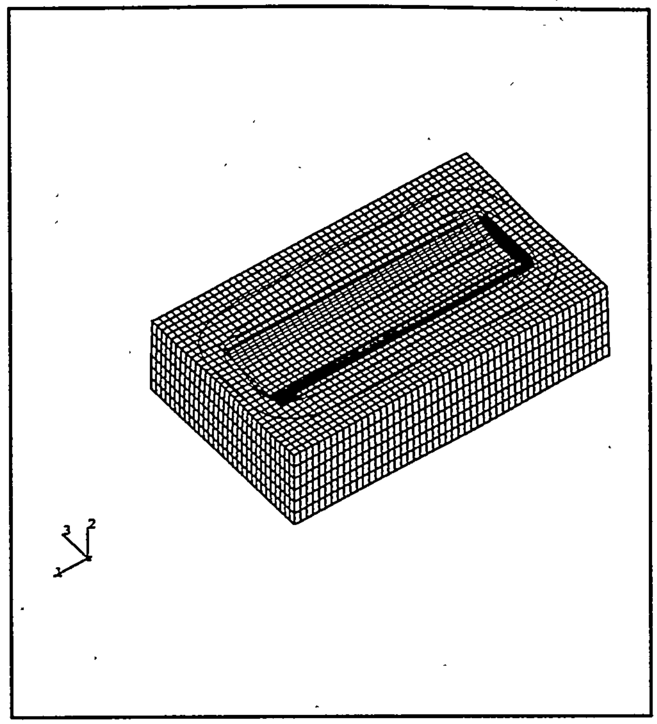

Figure 7. Crush Pad Indentation from Cask Side Drop

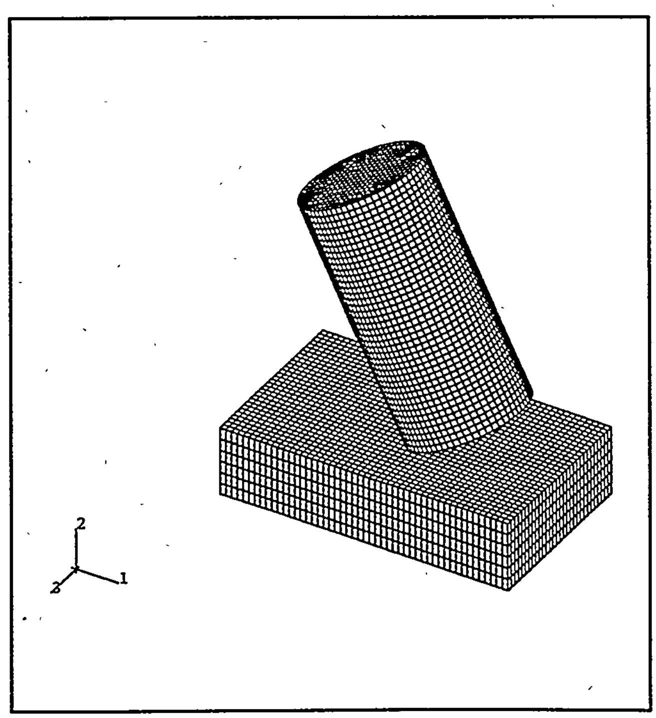

Figure 8. Finite Element Model of Cask Corner Drop

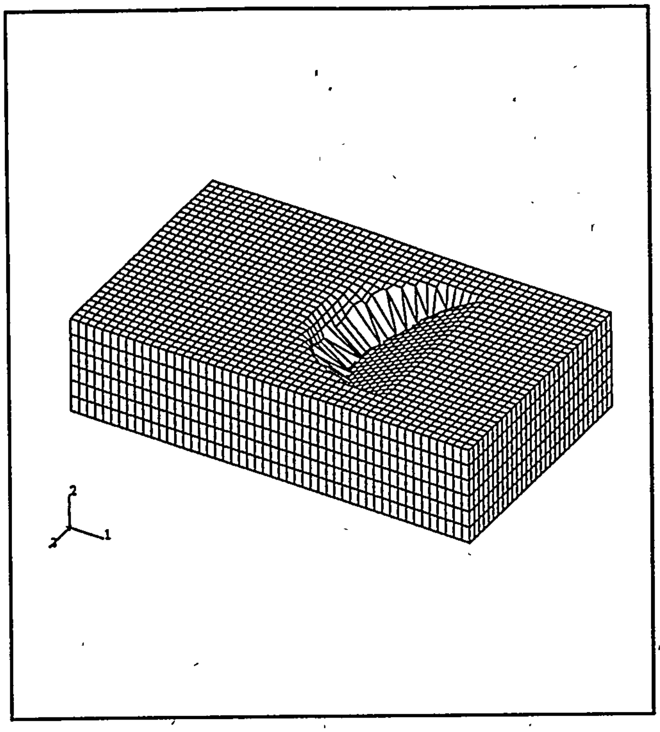

Figure 9. Crush Pad Indentation from Corner Drop