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EVALUATION OF IMPACT TESTS OF SOLID STEEL BILLET ONTO CONCRETE PADS, AND APPLICATION TO GENERIC ISFSI STORAGE CASK FOR TIPOVER AND SIDE DROP*

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1. INTRODUCTION

Spent Fuel Storage Casks intended for use at Independent Spent Fuel Storage Installations (ISFSIs) typically are evaluated during the application and review process for low-energy impacts representative of possible handling accidents including tipover events. In the past, the analyses involved in these evaluations have assumed that the casks dropped or tipped onto an unyielding surface, a conservative and simplifying assumption. Since 10 CFR Part 72[1], the regulation imposed by the Nuclear Regulatory Commission (NRC), does not require this assumption, applicants are currently seeking a more realistic model for the analyses and are using analytical models which predict the effect of a cask dropping onto a reinforced concrete pad, including energy absorbing aspects such as cracking and flexure. In order to develop data suitable for benchmarking these analyses, the NRC has conducted several series of drop-test studies.

The tests described in this report were primarily intended to determine the response characteristics of concrete pads during tipover and side impacts of a solid steel billet onto the pads. This series of tests is fourth in a program of tests funded by the NRC; all four series of tests address issues of impact involving spent fuel storage casks. The first series was performed in March 1993 by Sandia National Laboratories (SNL) and involved five end-drops of a billet, nearly identical to the one used in the present series, onto a variety of surfaces from a height of .457 m [18 in.]. The second series of tests was performed between July and October 1993, and involved four end-drops of a near-full-scale empty Excellox 3A cask onto a full-scale concrete pad and foundation, or onto an essentially unyielding surface, from heights ranging from .457 m [18 in.] to 1.52 m [60 in.], and was conducted by the British Nuclear Fuels Limited in Winfrith, England. (Two of the drops in the second series were sponsored by Electric Power Research Institute.) The third test series was performed in September 1993 by SNL, and involved eight further end-drop tests of the billet onto concrete pads. These pads were cast on engineered fill resting on undisturbed soil; billets were dropped from heights

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[1]United States Code of Federal Regulations Title 10, Part 72.

ranging from .457 m [18 in.] to 1.83 m [6 ft.]. The first three series of tests are described in a Sandia report by P. McConnell, et. al.[2]

The fourth test series included twelve drops of a solid steel cylindrical billet onto six reinforced concrete pads resting on undisturbed soil, and was conducted by Lawrence Livermore National Laboratory (LLNL) in February 1996. The size of the billet was selected to match the billet used in the Series 1 and 3 tests; it is roughly a 1/3-scale model of a spent fuel storage cask (the linear dimension is scaled). The dimensions of the concrete pads were selected to match the concrete pads used in the Series 1 and 3 tests; however, the outside pad dimension is somewhat larger because tests in this series are primarily side drops and earlier tests were end-drops. The concrete pads are roughly 1/3-scale models of the symmetry section of a hypothetical ISFSI concrete storage pad, including the reinforcing steel and gravel within the concrete. The data from this series of tests is provided in Reference 3.

This paper provides a method to evaluate the test results and a method to apply the results to an analysis of a full-size storage cask. An example application to a "generic" full-size cask is also provided, for tipover and low-velocity side impacts.

2. SUMMARY OF METHODOLOGY

In order to use the test data provided in Reference 3 to evaluate impact loads for a full-size storage cask, a series of steps needs to be taken. A brief summary of the required steps is given here.

Step 1: Rigid Body Motion of Billet Tests

The accelerometer data collected and reported in Reference 3 includes unfiltered data for twelve tests. The data must be filtered at an appropriate frequency in order to remove the vibratory component of the noise in the data such that the remaining deceleration represents the rigid body motion of the billet. This effort resulted in a filter frequency of 450 Hz for the side and tipover impact test data.

Step 2: Finite Element Model Representation of Billet Tests

The data collected and filtered in Step 1 is then used to determine the response characteristics of concrete pads during impact in order to develop a material model of the concrete pad to be used for analysis of low-velocity impact conditions. This task involves developing a finite element model of the billet and pad to be used in a series of dynamic analyses simulating the billet test conditions. Based on the series of simulations, a material model of the concrete pad is developed which characterizes the parameter of primary interest, that is, the rigid body g-loads corresponding to those determined in Step 1.

Step 3: Full Size Storage Cask Side Drop and Tipover Finite Element Simulations

The concrete pad properties developed in Step 2 are then utilized in a finite element simulation of a full-scale "generic" cask dropping sideways and tipping over onto a typical concrete storage pad. The "generic" cask FEM model did not include a detailed model of the basket; rather, a homogeneous basket model representing the appropriate density and approximate overall stiffness was used.

Step 4: Application of Finite Element Results to Future Quasi-Static Analysis of Basket

In order to evaluate the stresses in a secondary structure (such as the basket) resulting from the g-loads predicted by an analysis of the primary structure (the cask), two options are available. One might choose to use the acceleration time history calculated in Step 3, and apply it directly in a dynamic finite element analysis of the basket. Or, the usual choice is to develop a model of the basket and perform a quasi-static analysis of the basket using the peak g-load of the cask rigid body motion determined in a similar process to that of Step 3. In this case, it is necessary to determine a dynamic amplification factor for the basket.

3. RIGID BODY MOTION OF BILLET TESTS

The purpose of filtering the dynamic test or analysis results of an impacting billet is to extract from the total dynamic response the rigid body or whole-body component of the response. A vibration analysis of the impacting billet and a Fourier-spectrum analysis of the impact response were performed. The analyses showed that the dominant frequencies of the rigid body response were lower than all significant natural vibration frequencies of the billet. Therefore, a low-pass filter was used for the filtering. A Butterworth filter was chosen because it produced minimal amplitude distortions. The time delay or phase shift produced by the filter in the filtered signal was eliminated by performing a backward filtering after the normal forward filtering. An 8th order filter was used to provide an adequately sharp cutoff of the high-frequency response. Using the Fourier spectrum of the dynamic response as a guide, the cutoff frequency for filtering the billet drop test results was set at 450 Hz. The cutoff frequency was located below the lowest significant vibration frequency of the billet and near the bottom of a valley of the Fourier spectrum, where the billet response is minimum. The adequacy of the cutoff frequency was confirmed by comparing the Fourier spectra of the filtered and unfiltered responses. The comparison showed that the filtering practically removed high-frequency responses representing the billet free vibrations but none of low-frequency response representing the rigid body motion.

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[2] McConnell, P., et al. "Test Report, Drop Tests Onto Concrete Pads for Benchmarking Response of Interim Spent Fuel Storage Installations," Sandia National Laboratory, September 1993.

[3] Witte, M., et al. "Low Velocity Impact Testing of Solid Steel Billet onto Concrete Pads," Lawrence Livermore National Laboratory, UCRL-ID 126274, March 1997.

4. FINITE ELEMENT MODEL REPRESENTATION OF BILLET SIDE DROP AND TIPOVER TESTS

A finite element model with the steel billet, concrete pad and the subgrade soil was constructed using the TrueGrid[4] mesh generator. The model takes advantage of symmetry planes that exist in this drop orientation; thus, only a quarter model is needed for the billet side drop impact analysis. A half model is used for the billet tipover analysis. The impact event is simulated with the nonlinear finite element code DYNA3D[5]. Slide surfaces with voids are placed in between the steel billet and the concrete pad and in between the concrete pad and the subgrade soil. No information regarding the value of coefficient of friction in between those sliding surfaces is available from the test. A coefficient of friction of 0.25 is therefore assumed for both slide surfaces. A non-reflecting boundary condition is also imposed on three faces of the soil model, except on the symmetry face, to better represent the true situation of infinite soil domain with no stress wave reflection from soil medium.

The billet side impact is simulated by imposing a uniform initial velocity on the billet; the tipover is simulated by applying an initial rotational velocity to the billet.

4.1. Material Model Representation in the Finite Element Model

Steel Billet

The material of the test billet was ASTM 576 Grade 1045 steel, with a tensile strength of 6.69 x 108 N/m2 [97 ksi] and a yield strength of 4.14 x 107 [60 ksi] to 4.62 x 107 N/m2 [70 ksi].

Concrete Pad

The concrete pad is modeled using a constitutive model based on a concrete which was developed by LLNL in 1988. Material Model 16 in DYNA3D has the capability of modeling strain-rate effects for the yield strength via the use of a load curve multiplier. Mode II.B of Material Model 16 is used; the properties used are provided in Reference 6.

Six concrete pads were poured for the twelve drop tests used in this test series. Each pad was used twice, so for the second test on each pad, the pad had been partially damaged by the previous drop as listed in Table 1. An attempt was made to minimize the effect of the damage on the drop results, by turning the billet by 90˚, and by dropping the lower velocity drops prior to the higher velocity. In one case only a higher velocity drop was made first in order to evaluate the effect of the cracked pad on the result.

TABLE 1. CONDITION OF CONCRETE PAD FOR SIDE AND TIPOVER DROP TESTS

Side Drop Billet Tests		
Test ID	**Condition of Pad**	**Drop Height**
#3	undamaged	.457 m [18 in.]
#5	undamaged	.457 m [18 in.]
#10	damaged (reused the pad from test #9)	.457 m [18 in.]
#4	damaged (reused the pad from test #3)	.91 m [36 in.]
#7	undamaged	.91 m [36 in.]
#9	undamaged	.91 m [36 in.]
#6	damaged (reused the pad from test #5)	1.83 m [72 in.]
#8	damaged (reused the pad from test #7)	1.83 m [72 in.]

Tipover Billet Tests		
Test ID	**Condition of Pad**	**Drop Height**
#11	undamaged	CG over corner tip
#12	damaged (reused the pad from test #11)	CG over corner tip

Subgrade Soil Representation

Soil properties vary widely from one place to another; therefore, it is difficult to select a soil model that covers most situations. In light of its uncertainty, it was decided to use the simple elastic model to represent subgrade soil. Bowles[7] listed some representative ranges of soil values; there is a wide variation of soil properties, even in the elastic range.

A few analytical simulations of the billet end-drop on concrete pad, on top of soil were made with varying soil elastic properties. Young's Modulus was varied from a low of 4.14×10^7 N/m^2 [6 ksi] to a high of 4.14×10^9 N/m^2 [600 ksi] and υ was varied from 0.2 to 0.4. These variations in soil elastic properties produced little differences in the predicted initial 'peak' deceleration of the billet. Preliminary results on billet deceleration are derived from the raw accelerometer data for the three billet end-drops onto concrete pad. Results show that all are within experimental uncertainty band, despite the three very different soil types: (1) decomposed granite-type soil, (2) loam-type soil (both drops were performed at the Sandia test site), and (3) wet clay-type soil at LLNL's Site 300. These results also suggest that the subgrade soil under the concrete pad has a secondary effect on the initial response of the billet. Thus, it was decided that an elastic soil model with $E = 4.14 \times 10^7$ N/m^2 [6 ksi] and $\upsilon = 0.3$ would be used in this simulation.

[4]TrueGrid, XYZ Scientific Applications, Inc., Livermore, CA.

[5]Whirley, R. G. "DYNA3D, A Nonlinear, Explicit, Three-Dimensional Finite Element Code for Solid and Structural Mechanics-User Manual, " Lawrence Livermore National Laboratory, UCRL-MA-107254 , Rev. 1, 1993.

[6] Witte, M., et al. "Evaluation of Low-Velocity Impact Tests of Solid Steel Billet onto Concrete Pads, and Application to Generic ISFSI Storage Cask for Tipover and Side Drop," Lawrence Livermore National Laboratory, UCRL-ID 126295, March 1997.

[7]Bowles, J. E. *Foundation Analysis and Design*, 2nd ed., McGraw Hill, 1977, p. 35.

4.2. Steel Billet Impact Finite Element Simulation Results

The analysis results for the steel billet impact simulation include the response calculated by the finite element code at each calculational time step (3.7 x10^{-6} seconds). The analysis results were filtered using the same filtering technique which was used for the test results: a Butterworth low-pass filter with a cutoff frequency of 450 Hz was used. (This is an eighth-order Butterworth filter.) The data processing software DADiSP 4.0 was used, both for the analysis data and for the test data. Results are provided in Tables 2 and 3.

By applying the “dynamic” material properties listed in the previous section, the steel billet impact simulation results are tabulated below for different billet side drop height.

Tables 2 and 3 show that the finite element simulation results of the billet impact event for three drop heights and one tipover impact using the material properties described are in good agreement with test results. The predicted g-loads are typically (not always) slightly lower than the tested g-loads for the same filter frequency. This could be due to a number of factors, including lack of reinforcing steel in the concrete model, and the fact that the concrete used in the analytical model is representative of 2.90 x 10^7 N/m^2 [4200 psi] compressive strength concrete, whereas the concrete used for the actual test conditions was 3.08 x 10^7 N/m^2 [4460 psi] compressive strength concrete.

Figures 1 and 2 show billet tipover test data and analysis results.

TABLE 2. MAXIMUM BILLET SIDE DROP ACCELERATION TEST VS. SIMULATION

Billet drop height	**Test data from channel A3, filtered at 450 Hz**	**Finite element analysis simulation, filtered at 450 Hz**
.457 m [18 in.] (Test #3)	108.2 g	
.457 m [18 in.] (Test #5)	86.0 g	104.3 g
.457 m [18 in.] (Test #10)	125.5 g	
.91 m [36 in.] (Test #4)	110.0 g	
.91 m [36 in.] (Test #7)	not available	139.5 g
.91 m [36 in.] (Test #9)	125.2 g	
1.83 m [72 in.] (Test #6)	206.7	
1.83 m [72 in.] (Test #8)	197.0	182.6 g

TABLE 3. MAXIMUM BILLET TIPOVER ACCELERATION TEST VS. SIMULATION

Test # / Channel #	**Test data, filtered at 450 Hz**	**Finite element analysis simulation, filtered at 450 Hz**
Test #11/ Channel A1	237.5 g	
Test #12 / Channel A1	213.6 g	
Test #11 / Channel A5	231.5 g	233.1 g
Test #12 / Channel A5	213.0 g	

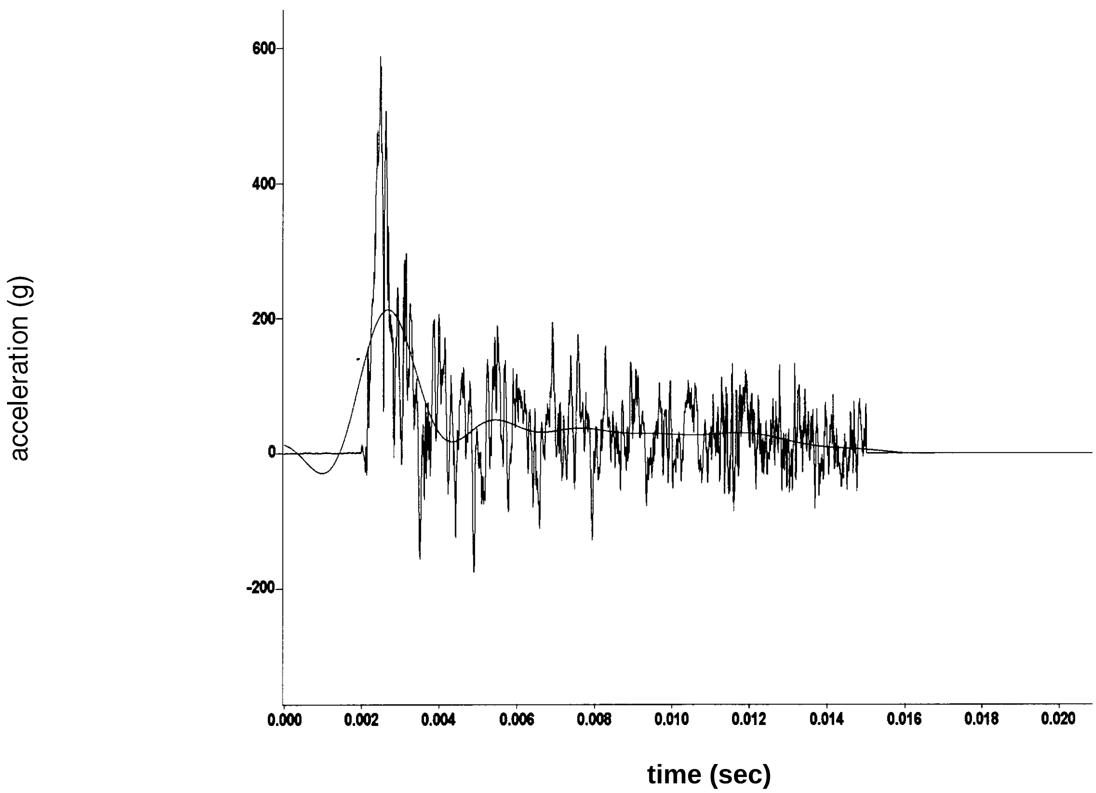

FIGURE 1. TEST #12, BILLET TIPOVER, TEST DATA FROM CHANNEL A5:
UNFILTERED AND FILTERED AT 450 HZ, MAX A = 213.0G

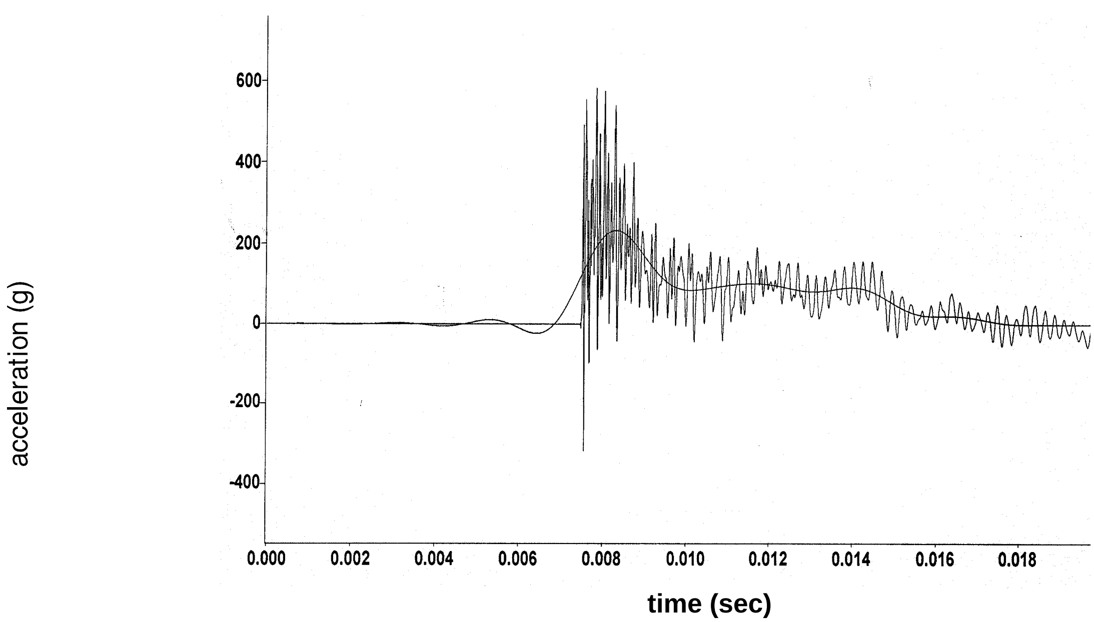

FIGURE 2. BILLET TIPOVER ANALYSIS RESULTS, UNFILTERED
AND FILTERED AT 450HZ, MAX A =233.1G

5. FULL SIZE "GENERIC" STORAGE CASK SIDE DROP AND TIPOVER FINITE ELEMENT SIMULATIONS

5.1. Selection and Modeling of "Generic" Cask

A storage cask using representative dimensions, material properties, and cask weight was selected for this study. The cask selected is referred to in this report as a "generic" cask, and is shown in Figure 3. The "generic" storage cask tipover and side drop were simulated using the concrete and soil material property representations described in Section 4.1 with the DYNA3D finite element code.

The finite element model for the "generic" cask is shown in Figure 4. Only the essential structural members of the cask are included in the model. Components such as weather cover, trunions, and neutron shield are neglected. The basket structure and fuel assemblies are modeled as a solid cylinder which occupies the region within the cask cavity that is occupied by fuel. The weight distribution of the cylinder representing the basket structure follows closely to that of a typical basket with fuel assembly, whereas the stiffness of the cylinder is set at $E = 1.93 \times 10^{10}$ N/m^2 [2.8×10^6 psi] to reflect the flexible nature of the basket structure. As can be seen in Figure 4, the basket is modeled in sections in order to facilitate data reduction at various locations along the basket length.

The sliding interfaces are placed between the basket structure and the inner surface of the cask wall, between the cask and the concrete pads, and between the concrete pad and the soil. The concrete pad dimensions used in the simulation are 4.06-m wide [160-in. wide], 5.08-m long [200-in. long], and .91-m thick [36-in. thick]. The finite element model takes advantage of the symmetry plane that exists along the axis of the cask. Again, non-reflecting boundary conditions are imposed on all faces of the soil model to prevent artificial stress wave reflections from the boundaries of the soil model.

The cask tipover impact is simulated with DYNA3D by imposing an angular velocity of 1.729 radians/sec to the entire cask body. The center of rotation is set at the edge of the cask bottom. DYNA3D calculates the initial velocity components associated with each node for this rotational motion.

5.2. Finite Element Tipover and Side Drop Simulation Results

The maximum rigid body decelerations are obtained from the simulations for the side drop and tipover of the "generic" cask. The analysis results from these simulations have been filtered with a process similar to the billet analysis filtering process. The cutoff frequency for filtering the generic cask analysis results was set at 350 Hz, because the lowest cask vibration frequency is about 100 Hz less than the corresponding frequency of the billet. The maximum decelerations averaged through the lid of the cask for the tipover, and through the cask wall for the side drop are listed in Table 4.

6. APPLICATION OF FEM RESULTS TO FUTURE STATIC ANALYSIS OF BASKET

In order to apply the g-load calculated for the storage cask body to a secondary structure such as a basket, several options are available. An analyst might take the calculated acceleration time history of the cask body and apply it directly to the secondary structure in a dynamic analysis. Or, an analyst may choose to perform a quasi-static analysis of the secondary structure, in which case a dynamic amplification factor needs to be applied to the static load on the basis of the dynamic properties of the secondary structure and pulse characteristics of the rigid body motion. In the absence of information about the vibration period of the secondary structure, a dynamic amplification factor of two is appropriate.

7. SUMMARY AND CONCLUSIONS

Twelve tests were performed at LLNL to assess loading conditions on a spent fuel cask for side drops, end drops and tipover events. The tests were performed with a 1/3-scale model billet and a 1/3-scale model concrete pad to benchmark the structural analysis code DYNA3D. The side drop and tipover test results are discussed in this report. The billet and test pad were modeled with DYNA3D using material properties and techniques used in earlier tests. The peak or maximum deceleration test results were compared to the simulated analytical results. It was concluded that an analytical model based on DYNA3D code has been adequately benchmarked for this type of application.

A "generic" or representative cask was modeled with the DYNA3D code and evaluated for ISFSI side drop and tipover events. The analytical method can be applied to similar casks to estimate impact loads on storage casks resulting from low-velocity side or tip impacts onto concrete storage pads.

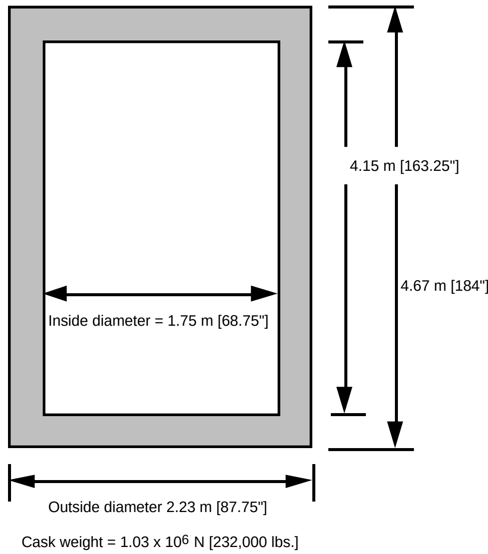

FIGURE 3. GENERIC CASK DIMENSIONS

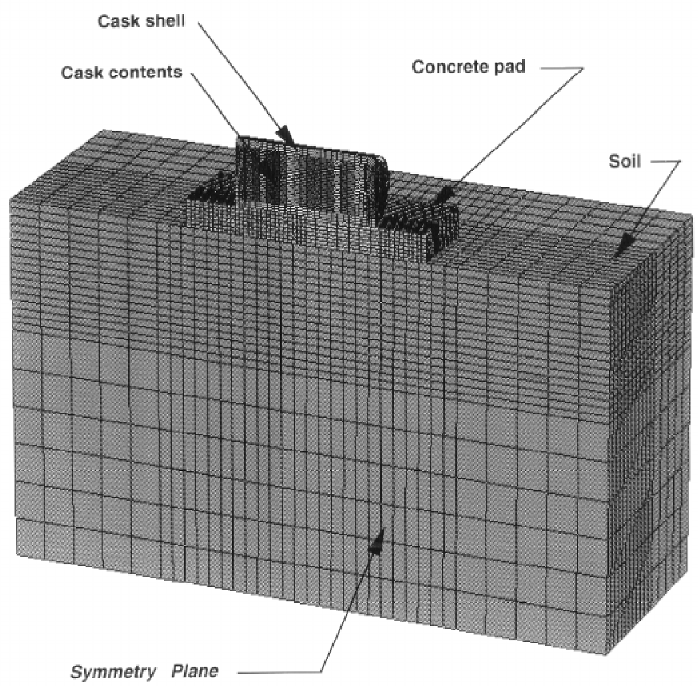

FIGURE 4. FINITE ELEMENT MODEL OF “GENERIC” STORAGE CASK,
SIDE DROP AND TIPOVER ONTO CONCRETE PAD AND SOIL

TABLE 4. ISFSI GENERIC CASK TIPOVER AND SIDE DROP ANALYSIS RESULTS

	Finite element analysis simulation, filtered at 350 Hz	**Location of reported g’s**
Tipover	66.7 g	Averaged through the cask lid
1.83 m side drop	53.8g	Averaged through the cask wall

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