A Validation Case Study: Steel Billet Drop Tests and Simulations as Reported in NUREG/CR-6608

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Abbreviations:
AIAA (American Institute of Aeronautics and Astronautics)
CSM (Computational Solid/Structural Mechanics)
ISFSI (Independent Spent Fuel Storage Installations)
LLNL (Lawrence Livermore National Laboratories)
LSTC (Livermore Software Technology Corporation)
NRC (Nuclear Regulatory Commission)
USACM (United States Association for Computational Mechanics)

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ABSTRACT

Before performing safety assessments of spent fuel storage casks in drop and tipover accident simulations, method validation calculations are required. The validation process is outlined by the Nuclear Regulatory Commission (NRC) [Tang, et al., undated], and specifically requires the satisfactory replication of the steel billet drop tests, reported in NUREG/CR-6608 (UCRL-ID-129211) [Witte, et al., 1998]. In addition to reporting the test results in NUREG/CR-6608, Witte, et al. also provide simulations of the tests using the Lawrence Livermore National Laboratory explicit finite element code DYNA3D [Whirley, 1993]; several other organizations have used the Livermore Software and Technology Corporation code LS-DYNA [Hallquist, 1999]. Although other explicit finite element codes would also be applicable, the material model parameters provided for the concrete pad, upon which the billets are dropped, in NUREG/CR-6608 are specific for the Concrete/Geological Material, i.e. Material Type 16, in DYNA3D and LS-DYNA. This sole fact provides a great incentive for analysts to use DYNA3D or LS-DYNA.

This manuscript briefly reviews the test configurations and results with recommendations on which configurations and results should be emphasized in comparisons with simulations. Next a brief review of the simulations presented in NUREG/CR-6608 with comments on the modeling and results and suggested improvements is provided. Then comments are provided on the utility of these results, both experimental and numerical, as a validation of the methodology with a particular emphasis on how they extrapolate to the cases of interest for spent fuel storage casks. Finally, a series of recommendations are included that should be considered, and discussed, by analysts providing simulations for spent fuel storage casks and the authorities requiring the safety assessment of these casks.

INTRODUCTION

The US Nuclear Regulatory Commission (NRC) reviews and licenses the designs of spent fuel storage casks, in part, based on the performance of the casks under hypothetical accidents scenarios associated with handling and moving the casks to their concrete storage pads. These cask drop and tipover accidents represent the most severe mechanical loads that can reasonably be expected. Previous practice was to obtain maximum g loads for these accident scenarios assuming the storage pad was rigid, and apply these g loads in a quasi-static manner to demonstrate structural integrity. Recently the NRC sponsored several series of drop tests [McConnell, et al., 1993 and Witte, et al., 1997] to establish an experimental database that could be used by analyst to validate numerical methods (codes, models and techniques) that could then be applied to proposed cask designs.

As a demonstration of how the experimental data could be used by analysts, Witte, et al. [1997a] provided preliminary comparative analyses of the side and tipover steel billet drop tests performed by LLNL [Witte et al., 1997]. These preliminary comparative analyses were expanded to include all 12 steel billet drop tests performed by LLNL and are reported as NUREG/CR-6608 [Witte, et al., 1998]. Both reports include a method to evaluate the test results and a method to apply the results to a full-size storage cask.

The results and methods reported in NUREG/CR-6608 have become the de facto standard by which all other simulations and analyses of proposed Independent Spent Fuel Storage Installations (ISFSI) are judged. The report also provides a well documented case study of a validation procedure. It is the retrospective evaluation of this validation procedure, and suggestions of how such a procedure could be improved, that is the focus of the present article.

As computational mechanics enters its fifth decade it has perhaps reached a maturity where the focus is shifting from new methods development to assessment of the validity and range of applicability of the copious engineering results produced on a daily basis. The computational fluid dynamics community has recognized this shift in focus, and the corresponding need to define a methodology, toward assessment of results and through the AIAA has issued "Guide for the Verification and Validation of Computational Fluid Dynamics Simulations" (AIAA G-077-1998). A parallel effort in computational solid/structural mechanics (CSM) has been initiated by the United States Association for Computational Mechanics (USACM).

APPROACH

The process of verification and validation of simulation results is perhaps easier to define than implement, but we start with the definitions used by Roache [1998] in his seminal work:

Verification – solving the equations right

Validation – solving the right equations

Verification is a mathematical exercise that assures the user the program is correct while validation is an engineering exercise that assures the user the model is appropriate.

The two terms are always presented in the order verification and validation because it can be (is) folly to attempt any validation without verification of the program and algorithms used in the validation. This lack of verification is routine in practice, and in particular, was the case in NUREG/CR-6608 since no verification was reported. The authors of NUREG/CR-6608 placed their faith in the LLNL DYNA3D code developers, hoping that in their development they have provided sufficient verification of the many algorithms comprising DYNA3D. This code user placing of faith in the code developers is understandable, but not always excusable given the implications of the subsequent 'validated' results.

The focus of the present article is on the validation presented in NUREG/CR-6608 for the steel billet drop tests. Using the method described in the AIAA Guide, the system to be validated is broken down into its components and each component and its interaction is examined for validation.

DISCUSSION OF RESULTS

The goal of the validation study is to produce a model of the steel billet drop tests that satisfactorily replicates all of the experiments, i.e. the same numerical model with only the initial conditions changed from test-to-test. The following is a brief description of the tests.

Steel Billet Tests

A complete description of the tests and results is provided in Witte, et al. [1997]. A total of 12 test results were reported for three different impact orientations of the steel billet:

1. End Drop from 18 inches (Tests #1 and #2 onto Concrete Pad #5)
2. Side Drop from
    - 18 inches (Tests #3, #5, and #10 onto Concrete Pads #3, #4, and #2, respectively)
    - 36 inches (Tests #4, #7, and #9 onto Concrete Pads #3, #6, and #2, respectively)

- 72 inches (Tests #6 and #8 onto Concrete Pads #4 and #6, respectively)

3. Tipover (Tests #11 and #12 onto Concrete Pad #1)

Steel Billet Description. The solid steel cylindrical billet used in the tests was 72 inches long with a diameter of 20.25 inches and weighed 6475 lbf. The steel from which the billet was formed was specified as ASTM 576 Grade 1045 with a tensile strength of 97 ksi and a yield strength between 60 to 67 ksi.

Concrete Pad Description. Six concrete pads measuring 10 feet square and 12 inches thick were constructed with a target unconfined compressive strength of 3000 psi. Upper and lower surface steel reinforcement was used in constructing the pads and was specified to be a two way reinforcement grid at an 18 inch pitch using #3 rebar with a one inch cap of concrete between the surface and the reinforcement grid.

Soil Description. The soil where the concrete pads were poured was leveled, but the soil was not otherwise prepared nor characterized.

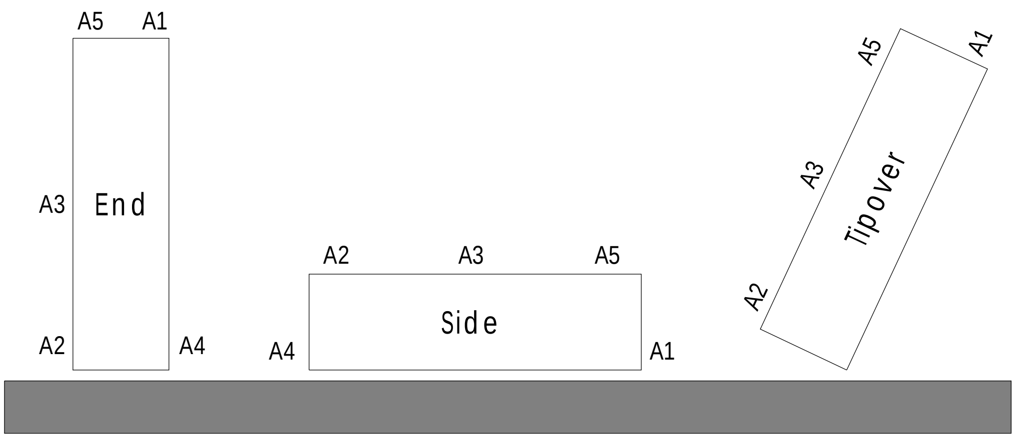

Figure 1. Steel billet test accelerometer locations.

Instrumentation Description. The active instrumentation consisted of accelerometers mounted on the sides and ends of the billets as shown in Figure 1 for the three impact orientations. Although the exact location and orientation of the accelerometers is not provided in Witte, et al. [1997], they were reported to be 2 inches from the top and bottom surfaces and at the mid-length of the cylinder and oriented to measure accelerations in a direction normal to the concrete pad [Witte, 1998].

Adequacy of the Test Description

Of the three types materials used in the tests, only the material characterization of the steel is adequate for material model validation. Although LLNL provides both 28 day and day of test (48 day) unconfined compressive strength data for the concrete slabs [Witte, et al., 1997], there is a wide array of geological material models that could be made to conform to this one number characterization. The lack of adequate concrete characterization is a serious shortcoming of these tests because the:

- concrete response is the dominate feature of the resulting experimental data,

- concrete pads are subjected to severe cracking as a result of the tests,
- the point of performing the tests was to provide data for characterizing impacts onto non-yield surfaces.

Inexplicably, no material characterization of the soil was attempted.

Adequacy of the Test Data

Generally the test data is quite good. An effort was made to perform at least two tests for each drop configuration so a limited assessment of repeatability can be made. Among the three drop test configurations, the side drop results show the most scatter, about 30% for the 18 inch drop height, because this configuration is particularly susceptible to non-planar impacts; so too is the end drop configuration but to a much lesser degree. The concrete pads were used for more than one test so there will be some question about the affects of existing damage in the concrete on the recorded accelerations. It is also a little disconcerting that the location of the accelerometers on the steel billet was not reported. A typical example of the test results is shown in Figure 2 which shows the acceleration history for gage A5 in the tipover Test #11 and the same response after the application of a low pass (450 Hz) filter; Figure B-50 in NUREG/CR-6608.

The experimental data was filtered using a low pass filter (450 Hz) to remove the higher frequency vibrations induced in the steel billet by the impact. Although those accustomed to such experimental acceleration records would not consider this data to be excessively noisy. The cutoff frequency of 450 Hz was selected based on the natural frequencies of the steel billet as listed in Table 6 of NUREG/CR-6608. The selection of this cutoff frequency greatly reduced the measure maximum acceleration, e.g. maximum of 200 g filtered compared to about 400 g unfiltered as shown in Figure 2.

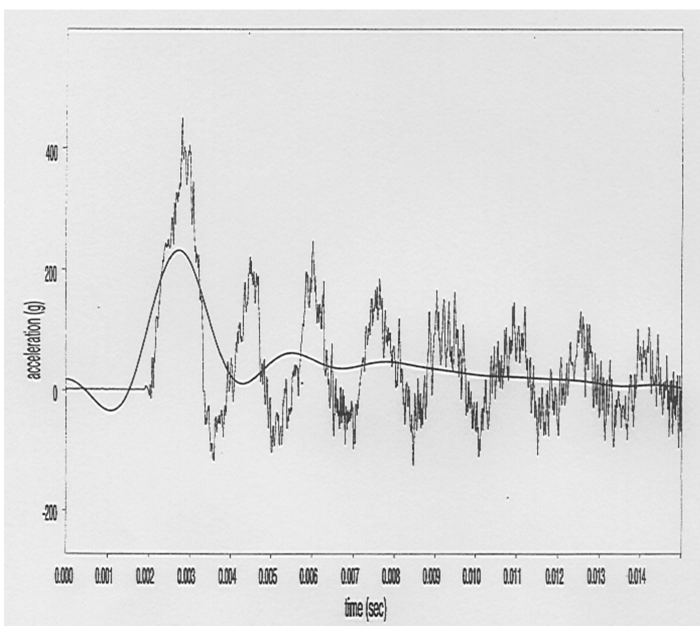

Figure B- 50 Test #11, Gauge A5 (tipover, filter cutoff: 450 Hz, maximum acceleration: 231.5g)

Figure 2. Recorded acceleration from tipover Test #11.

Description of the LLNL Billet Test Model

The description of the model used in NUREG/CR-6608 consists primarily of a picture of the mesh and listing the material properties. From the mesh picture and the cited mesh dimensions the reader can estimate the discretization used in the model, with the exception of the billet which appears to have a much finer mesh near the exterior surfaces. A soil island approach is used to limit the extent of the soil portion of the model and nonreflecting boundary conditions are specified for the island surfaces.

Elastic material models are used for the steel billet and the soil. No justification is provided for the use of an elastic model for the steel. The elastic model for the soil is justified by citing the uncertainty in the soil properties at the test site. The subsequent selection of the soil elastic properties was based on several side drop simulations, i.e. model calibration.

The material model selected for the concrete is the DYNA3D Concrete/Geological Material (Material Type 16) which as used in NUREG/CR-6608 is a rather complex model that uses two shear failure surfaces and a damage parameter to transition from the undamaged to damaged surfaces. The same material model is in LS-DYNA where it is referred to as a Pseudo Tensor Model (Material Type 16). This material model was selected because LLNL had previously contracted SRI International [Simons and Gefkin, 1988] to perform laboratory tests to characterize a concrete grout with similar unconfined compressive strength, and then fit the data using the Concrete/Geological Material. The resulting model fit is referred to as the Shippingport concrete model. Inexplicably, and unexplained, changes were made in the Shippingport concrete model for application to the steel billet drop test simulations.

Given the nearly identical unconfined compressive strength range for the Shippingport concrete laboratory measurements, 4.09 to 6.39 ksi for 18 specimens, and the unconfined compressive strength range for the drop test concrete slabs, 4.40 to 5.51 ksi for 12 specimens (minimum), the reasons for changing the SRI reported model parameters would need to be compelling, but are not provided in NUREG/CR-6608. Further, by providing only the modified model parameters, analysts are inhibited from using the SRI laboratory data to fit other concrete models. Indeed those seeking approval for proposed ISFSI seek out analysts that can provide simulations using the identical LLNL DYNA3D model and modified material parameters to the exclusion of other constitutive models.

Because the selected concrete model uses effective plastic strain as the damage parameter to transition from one shear failure surface to the other, the selection of the mesh size in the concrete slab can be important. Essentially, larger effective plastic strains will occur in meshes using smaller elements, i.e. with grid refinement. Thus the same material model parameters can produce different results based solely on mesh size. No such mesh sensitivity was reported in NUREG/CR-6608.

Another important aspect of the modeling that does not receive sufficient treatment in NUREG/CR-6608 are the contact interfaces used between the steel billet and concrete slab and concrete slab to soil interface. The report cites a sliding with void interface is used with a coefficient of friction of 0.25. It is not stated if the default penalty formulation is used or the optional Lagrangian formulation; the latter being preferred when large differences in stiffness exist across the interface as occurs between the concrete and soil. In an unreleased report, the first author reported a 14% increase in filtered acceleration response when the Lagrangian formulation was used in replicating the end drop configuration.

As mentioned above, the experimental data was filtered using a low pass filter (450 Hz) to remove the higher frequency vibrations induced in the steel billet by the impact. The test-to-simulation comparative method given in NUREG/CR-6608 required the simulation data to be filtered in the same manner as the test data. Comparisons are then to be made on the basis of maximum acceleration for each gage and test simulated. The corresponding comparison for the previously shown, Figure 2, tipover Test #11 is 231.5 g for the filtered test result and 244.7 g for the filtered simulation result. This represents only a 5.7% difference increase of the simulation result over the measurement. Figure 3 shows the corresponding two measured and simulated acceleration histories reproduced from Figures B-50 and D-5 in NUREG/CR-6608. It is difficult to see much similarity in the unfiltered measure and simulated responses.

The good agreement between the filtered measurement and filtered simulation results is further obscured by the fact that in the NUREG/CR-6608 tipover simulation the value used for the angular velocity was not reported, and subsequently it was discovered [Kennedy, 1998] that an incorrect value of the angular velocity was used 3.946 radians/second which is somewhat greater than the 3.365 radians/second obtained from the energy balance equations presented by KBS2 [1998] for the tipover configuration.

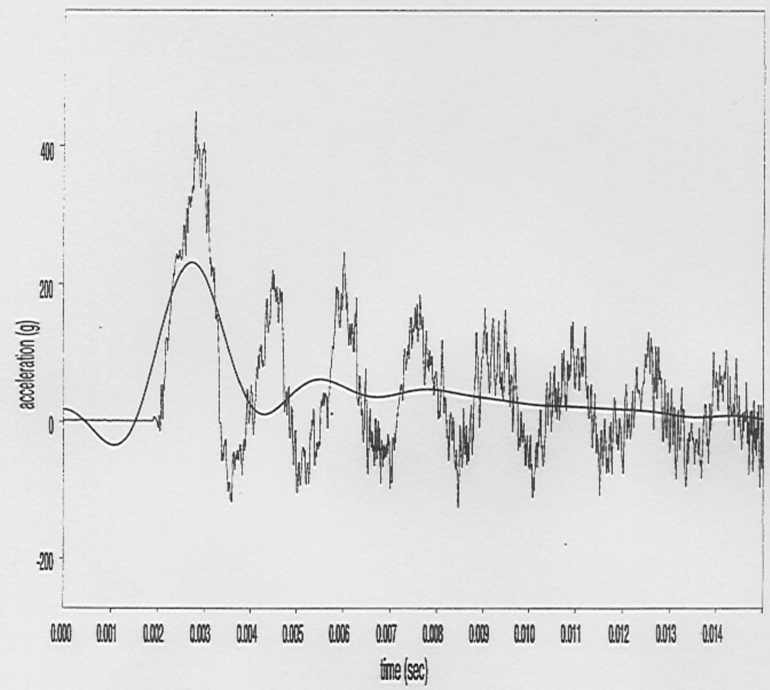

Figure B- 50 Test #11, Gauge A5 (tipover, filter cutoff: 450 Hz, maximum acceleration: 231.5g)

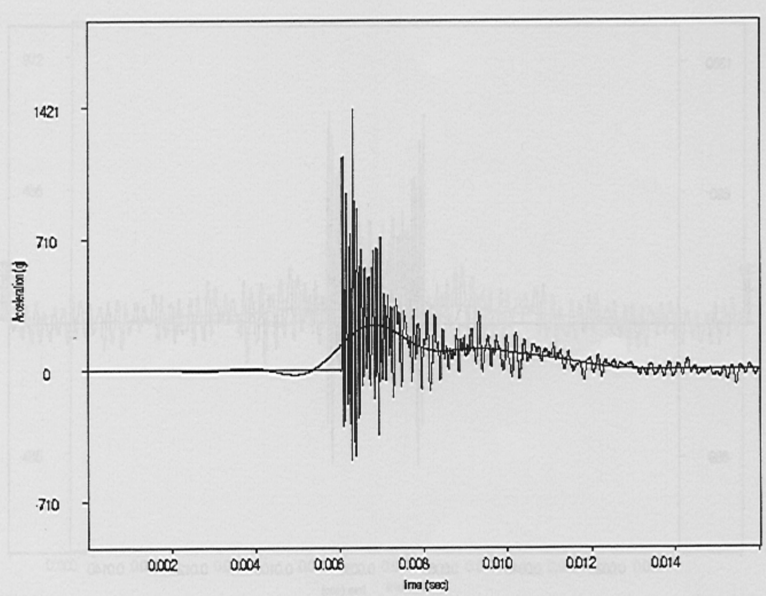

Figure D-5 Finite Element Analysis, Billet (tipover, filter cutoff: 450Hz, max. acceleration: 244.7g)

Figure 3. Comparison of measured and simulated acceleration for tipover Test #11.

SUMMARY AND RECOMMENDATIONS

The test data cannot be recommend as suitable for validation studies because the:

1 concrete pad material properties are inadequately characterized,
2 soil is uncharacterized,
3 accelerometer locations were not reported,
4 concrete pads were used repeatedly and thus damaged in an unquantifiable manner,
5 side drop test results are sensitive to the planarity of the impact.

The idea of using these steel billet drop tests as validation data for spent fuel casks is also questionable:

1 The outer protective structure of the casks is concrete. Why not drop concrete billets rather than steel billets? Damage to the concrete, both in the cask and pad, is the dominate feature of the measured response.
2 The steel billets weighed 6,475 lbf. The generic cask reported in NURGE/CR-6608 weighed 232,000 lbf. For the tipover configuration such a weight difference can translate into an increase in kinetic energy of about 150 times. The corresponding concrete pad damage would be significantly greater than that observed in the steel billet tests, and this would greatly effect the measured acceleration histories.

The utility, to other analysts, of the LLNL simulations of these tests can be improved, and some suggestions are made in the text. It is also recommended that part of the validation process include an all elastic material simulation of one or more of the steel billet tests. Since the billet and soil are already assumed to be elastic in NUREG/CR-6608, the addition of the concrete pad as an elastic material would greatly aid other analysts in benchmarking their models without the complications of the concrete pad material response.

Analysts should be encouraged to use the material testing results, as reported by SRI International [Simons and Gefkin, 1988], rather than specific material model inputs for the concrete since these constitutive models are subject to change, as codes are updated. This would also form an independent material model validation for the concrete, that is not currently included in the methodology. A similar validation of the soil should be considered.

General recommendations not covered in the text:

1 validation simulations that are intended to be a standard, or may become a de facto standard, should always be performed by more than one organization.
2 the same organization should not perform the tests and simulations,
3 those performing such simulations need to share not only the results but the input files so others can check the accuracy of questionable inputs; the NRC declined a request to allow LLNL to distribute their input files.
4 The collective knowledge gained in such simulations should be shared and distributed; in this case perhaps through a web page sponsored by the NRC.

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REFERENCES

"AIAA Guide for the Verification and Validation of Computational Fluid Dynamics Simulations," (G-077-1998) *AIAA Standards*, 40 pages, ISBN or Order Number: 1-56347-285-6, Copyright: 1998.

Hallquist, J.O. "LS-DYNA User's Manual (Nonlinear Dynamic Analysis of Structures in Three Dimensions)", Livermore Software and Technology Corporation, Version 950, May 1999.

KBS2 Final Report, "The Finite Element Analysis of Impact of Steel Billet onto Concrete Pad and Soil," May 1998.

Kennedy, J., personal communication, October 1998.

McConnell P., et al., "Test Report, Drop Tests Onto Concrete Pads for Benchmarking Response of Interim Spent Fuel Storage Installations," Sandia National Laboratories, Albuquerque, New Mexico, September 1993.

Roache, P, "Verification and Validation in Computational Science and Engineering" Hermosa Publications, Albuquerque, New Mexico, ISBN 0-913478-08-3, 1998.

Simons, J.W. and P.R. Gefkin, "Characterization of Grout for DYNA3D Model," SRI International, Final Report for SRI Project PYD-5077, April 1988.

Tang, D.T, M.G. Raddatz and F.C. Sturz, "NRC Staff Technical Approach for Spent Fuel Storage Cask Drop and Tipover Accident Analysis," Spent Fuel Project Office, U.S. Nuclear Regulatory Commission, Washington D.C.[Undated and unsourced document, probably circa 1997 from a conference proceedings.]

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

Witte, M.C., J.R. Squires, R.W. Carlson and J. Hovingh, "Low-Velocity Impact Testing of Solid Steel Billet onto Concrete Pads," Lawrence Livermore National Laboratory, UCRL-ID-126274, March 1997.

Witte, M., T.F. Chen, G.C. Mok, S.S. Murty, L.E. Fischer, "Evaluation of Low-Velocity Impact Tests of Solid Steel Billet onto Concrete pads, and Application to Generic ISFSI Storage Casks for Tipover and Side Drop," Lawrence Livermore National Laboratory, UCRL-ID-126295, Livermore, California, March 1997a.

Witte, M.C., J. Hovingh, G.C. Mok, S.S. Murty, T.F. Chen and L.E. Fischer, "Summary and Evaluation of Low-Velocity Impact Tests of Solid Steel Billets onto Concrete Pads," Lawrence Livermore National Laboratory, UCRL-ID-129211, February 1998. Prepared for the NRC and also appears as NUREG/CR-6608.

Witte, M.C., personal communication, October 1998.