STRUCTURAL CODE BENCHMARKING: IMPACT RESPONSE RESULTING FROM THE REGULATORY NINE-METER DROP

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ABSTRACT

Sandia National Laboratories' Transportation Technology Center has initiated a program in cooperation with Battelle Pacific Northwest Laboratories (PNL) to benchmark structural codes that are available to the nuclear materials transportation community. The program consists of the following five phases: 1) code inventory and review, 2) development of a cask-like set of problems, 3) multiple independent numerical analyses of the problems, 4) transfer of information, and 5) performance of experiments to obtain data for comparison with the numerical analyses.

The benchmark problems were selected to be cask-like and to require simulation of the nine-meter drop condition. Selected problems simulated end and side drop conditions with the more complex corner drop eliminated to reduce the computer costs associated with three-dimensional analysis.

The results showed that the codes were in reasonable agreement in simulating gross cask behavior such as impact duration and total deformations. As expected, variability in these parameters increased as the problems progressed from purely elastic behavior to elastic/plastic behavior. In addition, the analyses indicated that the local stresses and strains in high gradient regions are sensitive indicators of code behavior.

INTRODUCTION

The numerical analysis of structural problems is rapidly expanding and hence there has been a substantial effort directed at qualitatively evaluating and comparing available codes. Representative papers include Fong (1982)[1] and Dunder and Belonogoff (1980).[2] Fong compares eight finite element codes based on documentation quality, desirable features, user support and availability, element libraries, material libraries, and procedure libraries. Dunder and Belonogoff discuss the factors that should be used in selecting codes. These include service factors, evaluation criteria, program capabilities, efficiency, user convenience and protection, and developer reliability and responsiveness. These papers are of greatest value in establishing evaluation criteria and selecting codes for further evaluation.

There are also studies, of a more quantitative nature, where multiple codes are used to analyze a given problem. These include Crose and Fong (1984)[3] and Ball, et al., (1974).[4] In each of these papers finite element codes were used to analyze a specific problem and the results were compared. Since these papers present no experimental data, they rely on "consensus" solutions for statements of accuracy or applicability.

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In addition, there are also papers that address the analysis of the impact of nuclear shipping casks.[5,6,7] Yagawa, et al., (1984)[9] present a set of two end impact problems with plastic deformation and sliding interfaces. Solutions for several codes are presented without experimental confirmation. Adams, et al., (1981)[6] survey the available analytical techniques as well as existing cask designs. Static, dynamic, one-dimensional, and two-dimensional analyses of a steel clad lead cylinder end impact are presented. While this paper provides an excellent survey of existing techniques, it does not provide code specific information or experimental information. Counts and Payne (1977)[7] provided a review of three codes and six end impact tests. The codes were used to determine the lead slump. While limited in scope, this paper provides a methodology for code benchmarking.

To meet the specific needs of the nuclear materials transportation community, Sandia National Laboratories has initiated a program to benchmark publicly available structural codes. This program consists of the following five phrases: 1) code inventory and review, 2) development of a cask-like set of problems, 3) multiple independent numerical analyses of the problems, 4) transfer of information, and 5) performance of experiments to obtain data for comparison with the numerical analyses.

The selection of codes for evaluation and the development of benchmark problems undertaken jointly at Sandia and PNL were presented at the Government/Industry Joint Thermal and Structural Codes Information Exchange[8] in 1982. During this meeting industry participation was requested. This report will briefly summarize the benchmark problems and present the numerical analyses. The results that are presented include solutions obtained by SNL,[9] PNL,[10] GA Technologies,[11] and Century Research Center Corporation.[12]

BENCHMARK PROBLEM SELECTION

In order to meet the objectives of this program, benchmark problems were selected which would be cask-like in nature, test the capabilities of the surveyed codes, and yet be of sufficiently simple geometry that construction of models for experimentation would be straightforward.

The problems chosen for the benchmarking program reflect the regulations concerning the hypothetical accident condition of free drop in 10 CFR 71. This regulation states: "Free Drop--A free drop through a distance of 30 feet onto a flat, essentially unyielding horizontal surface, striking the surface in a position for which maximum damage is expected." This regulation specifies impact velocity and a target rigidity, but leaves the orientation of the package to be determined. Possible impact orientations are shown in Fig. 1. Since the cg over corner and arbitrary orientation impacts are inherently three-dimensional, only the end and side impacts were used in this benchmarking program. This allows evaluation of the various codes' material models and large deformation capabilities while maintaining relatively simple geometries.

To adequately model nuclear shipping casks, the codes should include elastic and elastic/plastic material models, sliding interfaces, and large deformation capability. These geometric and materials constraints resulted in the problem set shown in Fig. 2.

The parameter values requested from the numerical analyses of these problems were selected so that they could be readily obtained experimentally. The values requested represent those that can be obtained using high-speed photometrics measurement, such as impact duration and rebound velocity; those permanent deformations that can be obtained by post-test measurement; and time-dependent values of stress and strain.

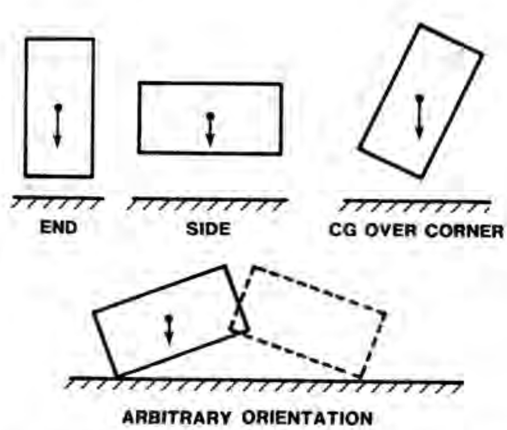


Fig. 1. Possible Impact Orientations for the Free Drop Test.

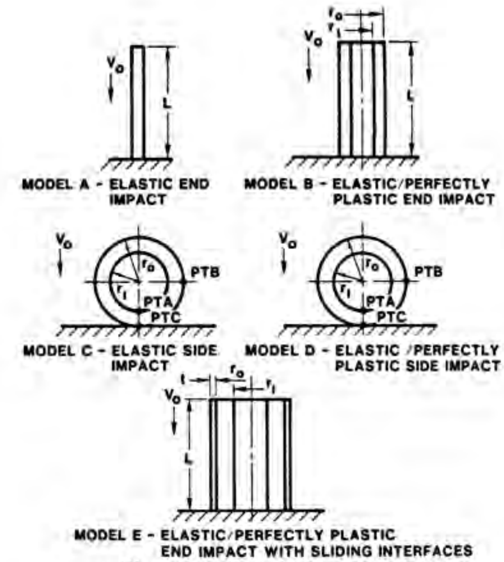


Fig. 2. Model Problem Set.

While these problems are intended to examine realistic physical phenomena, they are not all inclusive. As has been previously mentioned, three-dimensional problems are not addressed. The problems do not incorporate the separate phenomena associated with impact limiters such as crushable foam behavior, anisotropic material behavior as exhibited by wood, or the buckling of fins. The selected problems also do not attempt to simulate phenomena such as brittle fracture. Even with these exceptions, the problems represent a reasonable first pass at testing the ability of the codes to simulate realistic shipping casks.

RESULTS

The results obtained in this phase of the benchmarking study are indicative not only of the performance of codes, but also of the "typical" user. There has been no effort to reconcile differences in the solutions, but only to present the solutions obtained.

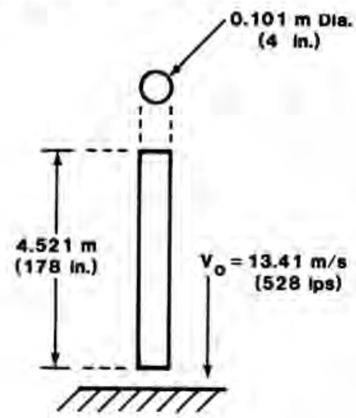
The solutions were obtained using the codes summarized in Table I. There are two independent solutions obtained using the HONDO II code. This allows the variation in the HONDO II solutions to be used as a measure of the variability expected strictly due to the users.

TABLE I

Code Matrix

Code	Type	Time Integration
HONDO II	Finite Element	Explicit
PISCES-2DELK	Finite Difference	Explicit
MANJUSRI-2D	Finite Difference	Explicit
ANSYS	Finite Element	Implicit
ABAQUS	Finite Element	Implicit

Model problem A is shown in Fig. 3. This model consists of an elastic steel bar undergoing end impact. This problem is the simplest of the problem set and also has an approximate analytical solution[13] based on Love's theory.[14] The approximation includes a term for radial displacement that is dependent on Poisson's ratio, radial location, and axial displacement gradients. The theory assumes that plane cross sections remain plane and that axial displacement is a function only of time and axial location. Based on this approximate theory, a plot of axial compressive stress as a function of distance from the impacting end at time T/4 is shown in Fig. 4.



MODEL A - END IMPACT OF ELASTIC ROD

Fig. 3. Model Problem A Represents a Thin Elastic Bar Striking the Target Axially. The properties are: Young's modulus = 1.9305 x 10^5 MPa, Poisson's ratio = 0.3 and density, = 8,027 kg/m^3.

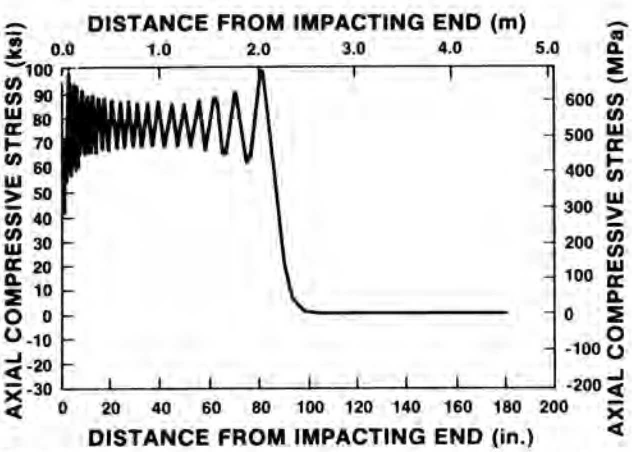


Fig. 4. Axial Compressive Stress Based on Love's Theory as a Function of Distance From the Impacting End at a Time Equal to One-Fourth of the Impact Duration

The corresponding code solutions for this problem, also at time T/4, are shown in Fig. 5 which plots axial compressive stress as a function of distance from the impacting end. These solutions compare well with the analytical solution, though the codes tend to average the stresses near the impacting end where the analytical solution shows stresses oscillating rapidly about the mean.

The impact duration, T, and rebound velocities are given in Table II with the means, μ, and standard deviations, σ. The standard deviations are less than 2 percent of the means. This indicates excellent consistency in the results.

A previous study[5] has shown that implicit integration schemes have greater oscillations in impact problems. This results in greater variability in stress/strain results and also makes predictions of rebound velocities more difficult. This is reflected in the lack of rebound velocities reported for the ANSYS results.

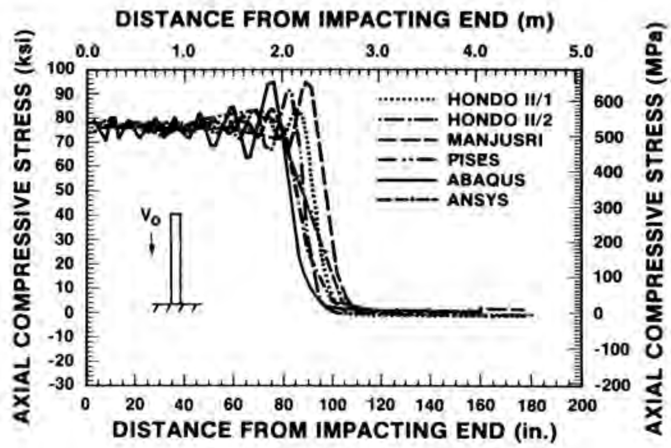


Fig. 5. Axial Compressive Stress as a Function of Distance From the Impacting End at Time Equal to One-Fourth of the Impact Duration.

TABLE II

Model A--End Impact of an Elastic Rod

Code/User	Impact Duration (ms)	Rebound Velocity (m/s)
HONDO II/I	1.86	13.46
HONDO II/2	1.86	13.1
MANJUSRI-2D	1.87	13.4
PISCES-2DELK	1.88	13.46
ANSYS	1.82	NR*
ABAQUS	1.86	13.27
μ Total	1.86	13.3
σ Total	0.020	0.15

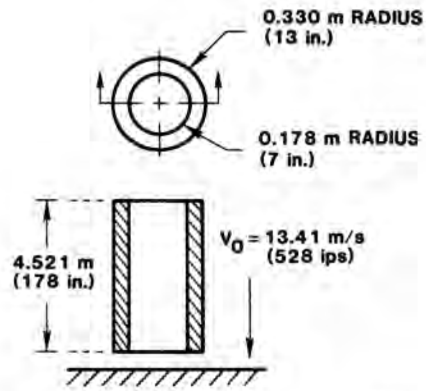
*Not reported

Model problem B is shown in Fig. 6. This model consists of an annular elastic/perfectly plastic steel cylinder undergoing end impact. This problem tests the ability to solve nonlinear problems involving the behavior associated with plastic deformation. The hoop strain at the outer radius of the impacting end is plotted as a function of time in Fig. 7.

The explicit integration codes had a variation in the maximum strain of 0.002, while the total variation in the maximum strain was 0.019. This difference is not mesh dependent since the ANSYS run had the same mesh as the HONDO II/2 run, and the ABAQUS run had the same mesh as the MANJUSRI and PISCES runs.

The tabulated values for impact duration, rebound velocity, and final axial deformation are shown in Table III. While the variation in tabulated results has also increased with the introduction of plasticity, there is still good agreement in the gross cask behavior. In particular, even though the localized hoop strains had a high variability, the standard deviation for the final axial deformation was only 5 percent of the mean.

Model problem C is shown in Fig. 8. This model consists of an annular elastic steel cylinder undergoing side impact. Plane strain is assumed in this problem. The horizontal stress at the inside radius, point A, is plotted as a function of time in



MODEL B - END IMPACT OF AN ELASTIC/PERFECTLY PLASTIC ANNULAR STEEL CYLINDER

Fig. 6. Model Problem B Represents an Annular Steel Cylinder Impacting the Target Axially. The steel is represented as an elastic/perfectly plastic material with the following properties: Young's modulus = 1.9305 x 10^5 MPa, Poisson's ratio = 0.3, density = 8,027 kg/m^3 and yield stress = 206.8 MPa.

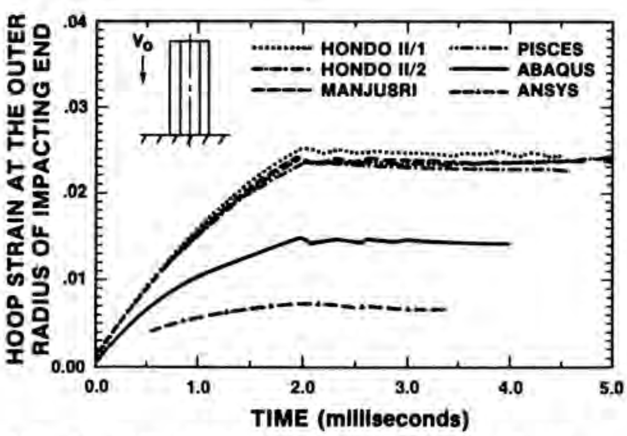


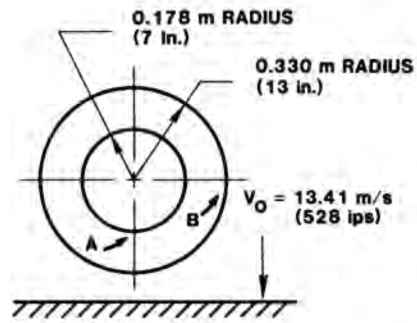
Fig. 7. Hoop Strain at the Outer Radius of the Impacting End as a Function of Time for Model Problem B.

TABLE III

Model B--End Impact of an Elastic/Perfectly Plastic Annular Steel Cylinder

Code/User	Impact Duration (ms)	Rebound Velocity (m/s)	Final Axial Deformation (m)
HONDO II/1	3.55	3.7	0.0157
HONDO II/2	3.907	3.63	0.0137
MANJUSRI-2D	3.48	3.48	0.0143
PISCES-2DELK	3.42	3.07	0.014
ANSYS	3.33	NR*	0.0146
ABAQUS	3.1	2.63	0.0153
μ Total	3.46	3.30	.0146
σ Total	0.27	0.45	.0008

*Not reported



MODEL C - SIDE IMPACT OF AN ELASTIC ANNULAR STEEL CYLINDER

Fig. 8. Model Problem C Represents the Side Impact of an Elastic Annular Steel Cylinder. The properties are: Young's modulus = 1.9305 x 10^5 MPa, Poisson's ratio = 0.3, density = 8,027 kg/m^3.

Fig. 9. The figure indicates a variation in maximum peak stress of 600 MPa (90 ksi). This is reasonable in a region where the radial stress gradient is approximately 36,000 MPa/m (130 ksi/in). The mesh sizes varied from three to six elements through the radius at the impact point. The variation, therefore, corresponds to an error in location of .017 m (.7 in) or less than the thickness of the smallest element.

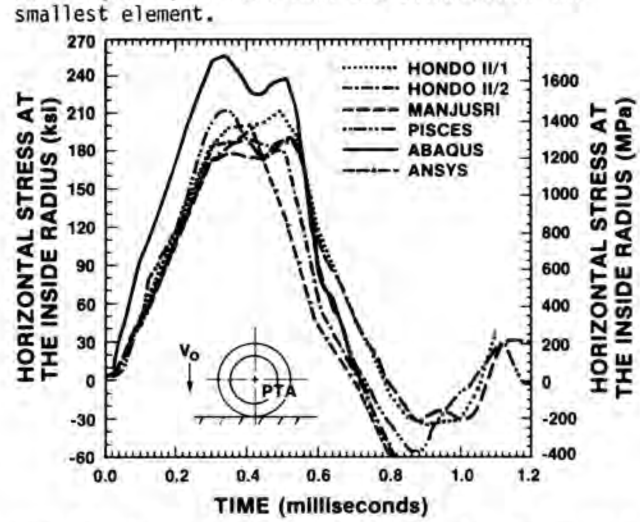


Fig. 9. Horizontal Stress at the Inside Radius as a Function of Time for Model Problem C.

Shown in Fig. 10 is the vertical stress at the outside radius, point B, as a function of time. In this problem the variation in maximum vertical stress is 345 MPa (50 ksi). Since this variation is between two of the HONDO II solutions the differences are considered to be user dependent.

The tabulated values of impact duration and average rebound velocity are given in Table IV. The standard deviations for both impact duration and rebound velocity are less than 5 percent of their respective means.

Model problem D, shown in Fig. 11, provides a direct measure of the effect of plasticity. The geometry, initial conditions, and meshes duplicate model

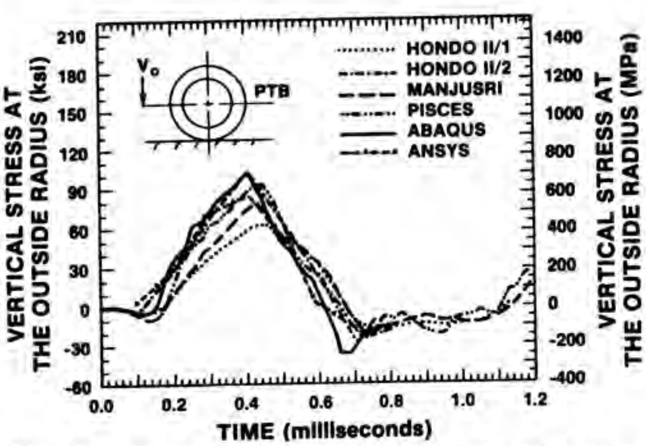


Fig. 10. Vertical Stress at the Outside Radius as a Function of Time for Model Problem C.

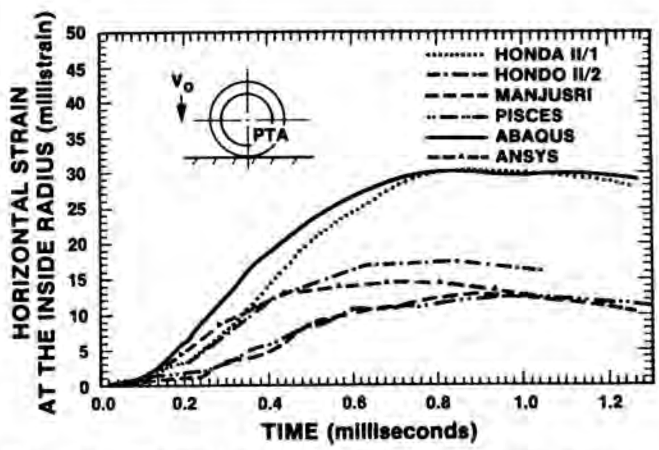


Fig. 12. The Horizontal Strain at the Inside Radius as a Function of Time for Model Problem D.

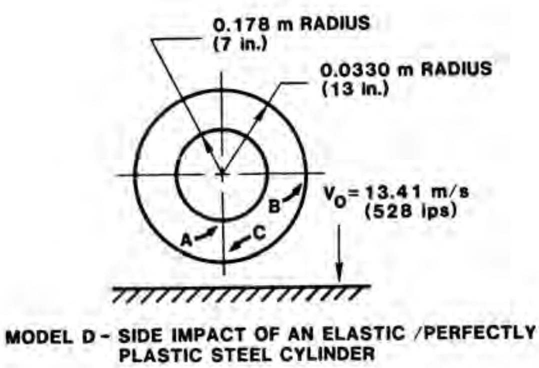


Fig. 11. Model Problem D Represents the Side Impact of an Elastic/Perfectly Plastic Steel Cylinder. The material properties are: Young's modulus = 1.9305×10^5 MPa, Poisson's ratio = 0.3, density = 8,027 kg/m^3 and yield stress = 206.8 MPa.

TABLE IV

Model C--Side Impact of an Annular Elastic Steel Cylinder

Code/User	Impact Duration (ms)	Rebound Velocity (m/s)
HONDO II/1	0.83	12.96
HONDO II/2	0.77	12.80
MANJUSRI-2D	0.82	13.2
PISCES-2DELK	0.79	13.4
ANSYS	0.727	NR*
ABAQUS	0.77	13.0
μ Total	0.78	13.1
σ Total	0.038	0.23

*Not reported

problem C with only the material model changed. The horizontal strain at the inside radius, point A, is plotted as a function of time in Fig. 12. The variability in peak strains was 130 percent for this elastic/perfectly plastic model. This is an increase from the variability in strains of 50 percent that would result from the peak stresses given for the purely elastic model problem C.

The vertical strain at the outside radius, point B, is plotted in Fig. 13. The variation in strains for this problem also are in excess of 100%.

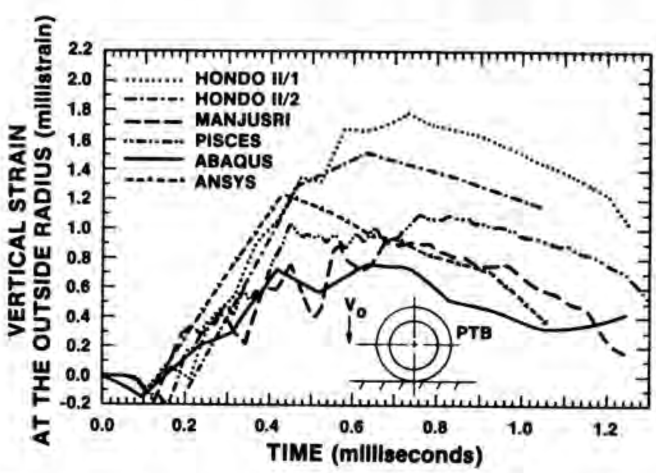


Fig. 13. The Vertical Strain at the Outside Radius as a Function of Time for Model Problem D.

The tabular data of impact duration, rebound velocity, and the horizontal and vertical ovalizations are given in Table V. The horizontal ovalization is defined as the ratio of the change in horizontal outside diameter to original diameter with a similar definition for the vertical ovalization. These data demonstrate two characteristics of this problem. These are: 1) permanent deformations are low, indicating that the problem is substantially elastic, and 2) even with localized strain variability in excess of 100 percent, the standard deviations of the horizontal and vertical ovalizations were less than 25 percent of the mean values. This is further improved to 12 percent if only the explicit integration results are considered. This indicates that the codes are still producing consistent gross cask behavior results for elastic/plastic problems with high stress gradients.

TABLE V

Model D--Side Impact of an Annular Elastic/Perfectly Plastic Steel Cylinder

Code/User	Impact Duration (ms)	Rebound Velocity (m/s)	Horizontal Ovalization (%)	Vertical Ovalization (%)
HONDO II/1	1.15	NR*	0.31	-0.93
HONDO II/3	1.052	3.378	0.36	-0.746
MANJUSRI-2D	1.22	3.84	0.30	-0.95
PISCES-2DELK	1.19	3.6	0.321	-0.95
ANSYS	0.9886	NR*	0.27	-0.695
ABAQUS	1.28	2.91	0.17	-0.98
μ Total	1.15	3.43	0.29	0.88
σ Total	0.11	0.40	0.063	0.12

*Not reported

Model problem E is shown in Fig. 14. This model consists of an elastic/perfectly plastic steel clad annular lead cylinder. The lead and steel are attached at a single point at the impacting end. Fig. 15 shows the hoop strain in the cladding as a function of time. The results are comparable to those for model problem B, with the strains a factor of three higher than those shown in Fig. 7. Figure 16 shows the axial strain in the lead.

Tabular data for impact duration, rebound velocity, and axial deformations are given in Table VI. As in model problem D, the codes produce reasonably consistent results of gross cask behavior. The standard deviations are less than 28 percent of their respective means. This is reduced to 14 percent if the results are restricted to the explicit integration codes.

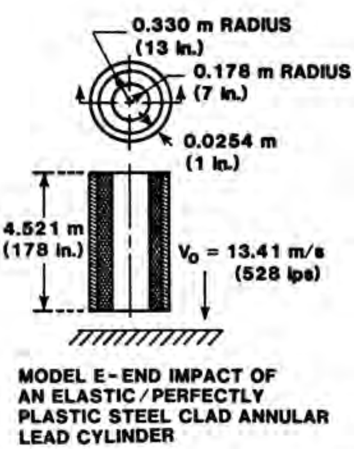


Fig. 14. Model Problem E Represents the End Impact of an Elastic/Perfectly Plastic Steel-Clad Annular Lead Cylinder. The material properties for the steel are: Young's modulus = 1.9305 x 10^5 MPa, Poisson's ratio = 0.3, density = 8,027 kg/m^3 and yield stress = 206.8 MPa. The properties for the lead are: Young's modulus = 1.3789 x 10^4 MPa, Poisson's ratio = 0.45, density = 1.135 x 10^4 kg/m^3 and yield stress = 13.78 MPa.

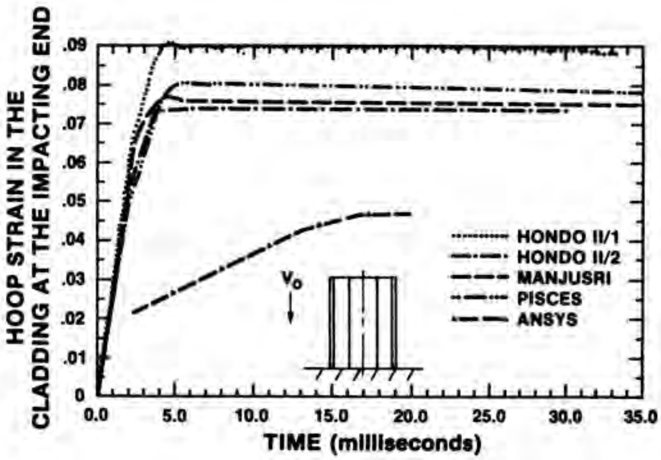


Fig. 15. Hoop Strain in the Steel Cladding at the Impacting End as a Function of Time for Model Problem E.

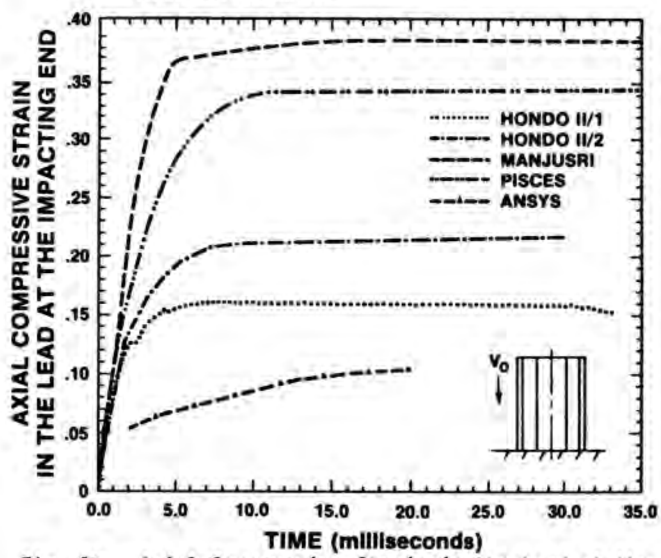


Fig. 16. Axial Compressive Strain in the Lead at the Impacting End as a Function of Time for Model Problem E.

TABLE VI

Model E--End Impact of an Elastic/Perfectly Plastic Steel Clad Annular Lead Cylinder

Code/User	Impact Duration (ms)	Rebound Velocity (m/s)	Axial Lead Deformation (m)	Axial Steel Deformation (m)
HONDO II/1	30.0	NR*	0.192	0.0184
HONDO II/3	30.2	0.804	0.198	0.018
MANJUSRI-2D	30.8	0.83	0.20	0.024
PISCES-2DELK	30.2	0.86	0.20	0.021
ANSYS	23.6	NR*	0.117	0.0328
μ Total	29.0	0.83	0.18	0.022
σ Total	3.01	0.028	0.036	0.006

*Not reported

CONCLUSIONS

The results obtained in this study indicate that all of the codes produce consistent results for purely elastic problems. The tabular data for impact durations and rebound velocities had standard deviations that were less than 5 percent of their respective means.

The introduction of plasticity and sliding interfaces increases the complexity of the problems and hence the variability in the results. The gross cask behavior, however, still remains reasonably consistent. This is reflected in the fact that the standard deviations for the impact durations, rebound velocities, and final deformations were less than 30 percent of the means. These standard deviations were less than 15 percent of the means when consideration was restricted to the explicit integration codes.

The only results with high variability were in high-gradient regions' stresses, and strains. As seen in the previous discussion, these variations were not reflected in the overall behavior of the cask. These regions are, however, useful in identifying differences in code behavior. They also indicate a need for experimental work to complement the existing analyses. A series of experiments are outlined in the following section.

FUTURE WORK

The primary objective in the proposed experiments is to obtain data which can be used in benchmarking codes with elastic/plastic material models and large deformation capability. To attain this objective, the proposed experiments will be scaled versions of model problems B and D. This will allow both end and side impact to be examined.

A secondary objective of this study will be the verification of existing scaling laws.[15] To meet this objective, a range of scaling factors will be used in designing the experiments. This will result in multiple versions of each model with variation only in the geometric scaling factors.

The experimental phase of this program should provide sufficient data to complete the benchmarking of structural codes with elastic/plastic material models and large deformation capability.

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