LA-UR- 04-6005

Approved for public release; distribution is unlimited.

Title: A Study of the Collapse Loading of Spherical Shells

Author(s): Jason E. Pepin
Ben H. Thacker
David S. Riha
Peter C. McKeighan

Submitted to: 46th Structures, Structural Dynamics, and Materials Conf.
Austin, Texas
April 18 - 21, 2005

Los Alamos NATIONAL LABORATORY

46th Structures, Structural Dynamics, and Materials Conference
18-21 April 2005
Austin, Texas

ABSTRACT

A Study of the Collapse Loading of Spherical Shells

J. E. Pepin	Los Alamos National Laboratory	jpepin@lanl.gov
B. H. Thacker	Southwest Research Institute	bthacker@swri.org
D. S. Riha	Southwest Research Institute	driha@swri.org
P. C. McKeighan	Southwest Research Institute	peter.mckeighan@swri.org

Submitted for the following special session in the NDA Forum:
Uncertainty Quantification's Role in Model Validation

Introduction

Current arms control agreements have provided the impetus for national directives to cease production of new strategic weapons and to end nuclear testing. This has placed a tremendous burden on the national laboratories for assuring stockpile certification. The Stockpile Stewardship Program's fundamental objective within the Department of Energy (DOE) is to maintain a high confidence in the safety, reliability, and performance of the existing U.S. nuclear weapons stockpile.

As such, enhanced evaluation capabilities are needed to quantify the effect of possible anomalies that may arise in a weapon (e.g., due to aging mechanisms), and assess its performance, safety and overall reliability. Validated numerical methods must be employed in determining the reliability of specific weapon components, including the overall weapon system. The validated numerical models must, however, be based on accurate information of each component's geometry and material properties in an aged condition. Once these variables are known, extrapolation of potential lifetime of the weapon can be determined with some level of confidence. The goal is to develop an engineering capability that provides a reliability-based structural evaluation technique for performing weapon reliability assessments. To enhance the analyst's confidence with these new methods, an integrated experiment and analysis project has been developed.

The focus of this project is to generate accurate probabilistic structural response simulations using numerical models of commercially available, stainless steel spherical marine floats, under collapse loads, and compare with experimental results. The spherical marine float geometry was chosen because of its simple shape, yet highly complex nonlinear deformation behavior, leading to complex states-of-stress. There is also a variability associated with geometry and mechanical properties of commercially available (i.e., off-the-shelf) marine floats. The variability is not uncommon, and principally due to numerous forming processes, different operators, etc., which bulk production operations employ for a single material lot.

The probabilistic analysis is performed using the NESSUS[1] probabilistic analysis software. NESSUS simulates uncertainties in loads, geometry, material behavior, and other user-defined uncertainty inputs to compute reliability and probabilistic sensitivity measures. To facilitate analyses of a broad range of problem types, a large number of efficient and accurate probabilistic methods are included in NESSUS. The probabilistic validation of the current work is performed in two phases. Initially, the deterministic spherical marine float model is validated against the experimentally observed collapse load. Next, variations in geometric shape parameters (i.e., surface geometry and thickness) are characterized using random fields to quantify test data from actual float geometry. Uncertainties in material properties (i.e., stiffness, strength, and flow) are also included in the probabilistic model. Finally, the probabilistic numerical model is validated by comparison to the predicted and observed variation in collapse load.

Deterministic Float Collapse Load Prediction

The spherical shells are commercially available marine floats commonly used by the petrochemical industries for liquid level measurements. The floats are manufactured from 304L stainless steel with a 9-inch outside diameter, 16-gage shell thickness, and no external piping connections.

The floats are manufactured by pressing flat circular plate stock into a hemispherical die using a hydraulic press. Once pressed, two hemispheres are placed on an automatic turning fixture and welded together. The pressing process creates regions in which the material properties are different due to different degrees of cold working. This variation was characterized using small compression coupons taken from different locations on a single float. As a result, the float model was divided into three different regions having different material properties. [2]

To characterize radius and thickness, twelve floats were cut in half orthogonal to the weld and measured using a coordinate measuring machine (CMM). This information was used to assess the variability in radius and thickness in both the longitudinal (pole to pole) and latitudinal directions. Based on our knowledge of the manufacturing process, we expected that latitudinal variations would not be significant, but that longitudinal variations could be significant.

For each hemisphere, two contour lines were measured in the longitudinal direction. The CMM measured 181 points along each contour line on both sides of the hemisphere. The distance between the inner and outer point was calculated to determine thickness and the midpoint was used to find radius. A limited number of measurements were also taken in the latitudinal direction. The measurements indicated that the random variation in thickness and radius is relatively constant along each line of latitude. [3] The CMM information was used to construct a one-dimensional random field model (pole to pole only) to simulate the spatial variability in radius and thickness. Further details of the material property testing and geometry characterization are given in Ref [3].

The simulation of a marine float being crushed between two platen strokes was performed using DYNA3D. [4] The float, shown in Figure 1, was meshed with 16,144 quadrilateral shell elements into three regions, the weld, a center band, and poles. This mesh refinement was selected after performing a mesh refinement study. [3] A tabular elastic-plastic material model was used to model the material in each region.

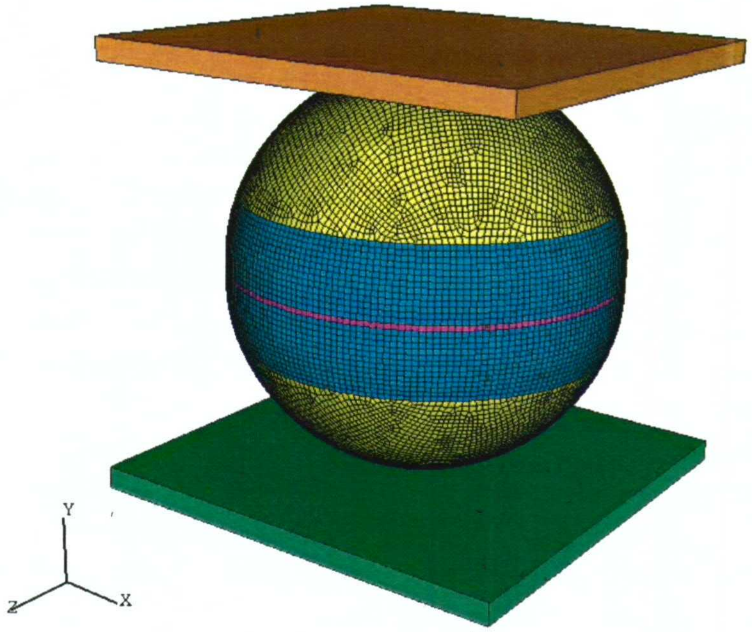


Figure 1: The mesh and platens used for the float collapse analysis.

Average (non-constant) values of thickness and radius from the CMM were used to create the nominal float mesh. A single rigid hexahedral element was used to mesh each of the platens. The bottom platen is held fixed and the top platen is moved toward the bottom platen at a constant velocity of 5 m/s to crush the float. This speed was selected after performing a series of runs at different speeds to balance computational efficiency (as fast as possible) and quasi-static response (as slow as possible).

To confirm the simulation results, twelve floats were crushed experimentally at Los Alamos National Laboratory (LANL). The load-stroke curves for these floats are compared to the predicted results (shown in red) in Figure 2. The hydraulic press used to crush the floats has a maximum stroke of four inches. Consequently, the floats were crushed in two steps resulting in the unloading and then reloading seen between 3.5 and 4 inches. Also, the load cell used with the hydraulic press could not measure forces greater than 55,000 lb_f and, therefore, did not measure the maximum force required to crush the floats.

To explore the effect of variations in radius and thickness, an additional simulation was performed using a perfect (constant radius and thickness) 16-gauge steel sphere. The load-stroke curve for the perfect sphere is shown in green in Figure 2. In spite of the experimental limitations noted above, the prediction using actual geometry data is qualitatively close to the experimental measurements. Because the collapse load (point at which the load first decreases) is clipped, however, the uncertainty in collapse load could not be measured from the twelve LANL experiments. This will be addressed in a subsequent section on validation testing.

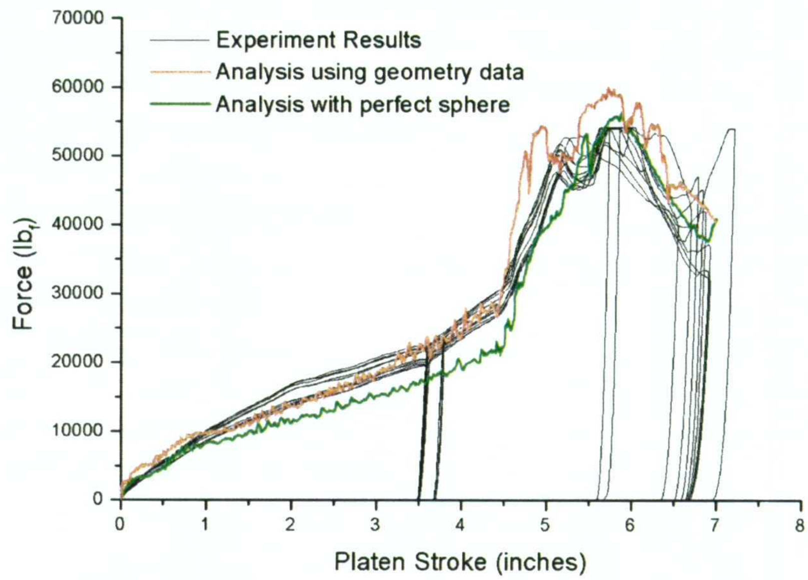


Figure 2: Comparison of experimental and deterministic force vs. stroke.

Probabilistic Float Collapse Load Prediction

The uncertainty analysis is performed using a probabilistic approach. The random variables are modulus of elasticity, yield stress, radius and thickness. The coefficient of variation (COV), which is the standard deviation divided by the mean value, for modulus of elasticity and yield stress are taken from Ref. [5] for 304L stainless steel. The yield stress random variable is designed to treat both hardening curves for the float, the center band and the top/bottom region, as one random variable. For this special case, an average initial yield stress is taken from the two curves and an average standard deviation is then calculated based on the COV. When the yield variable is perturbed during the probabilistic analysis, both hardening curves shift up or down with the perturbation.

Radius and thickness are modeled as random fields to account for the correlated spatial variations. The correlation structure was measured using the CMM data and used to generate the variance-covariance matrix. Based on the small fluctuations observed in the latitudinal direction CMM data, random variations in radius and thickness were only considered in the longitudinal (pole to pole) direction. The NESSUS random field preprocessor was used to perform the spectral decomposition. To retain 90% of the uncertainty (in L2-norm space) required only four vectors each for radius and thickness. Complete details of the probabilistic analysis and random field characterization are given in Ref. [3]. The random variable data used for the probabilistic analysis are summarized in Table 1.

The cumulative distribution function (CDF) of collapse load was obtained using the NESSUS software, shown in Figure 3. The y-axis is on a normal probability scale, i.e., zero implies zero standard deviations from the mean, which is equal to 50% probability. The mean-value (MV) first-order method was used to approximate the CDF with a small number of DYNA3D solutions. To verify the correctness of the approximate MV solution, a Latin Hypercube Simulation (LHS) was performed with 25 samples. As shown, the agreement between MV and LHS is relatively good near the zero standard normal point.

Table 1: Probabilistic data for the float model random variables.

Variable	Distribution	Mean	COV
E (psi)	Lognormal	2.8E+07	0.0238
R1 (in)	Normal	-39.153	-0.00137
R2 (in)	Normal	-8.9002	-0.00367
R3 (in)	Normal	-5.327	-0.00249
R4 (in)	Normal	2.127	0.00459
T1 (in)	Normal	-0.405	-0.0195
T2 (in)	Normal	0.0117	0.299
T3 (in)	Normal	0.305	0.0102
T4 (in)	Normal	0.0127	0.149
S_y (psi)	Normal	0	0.10

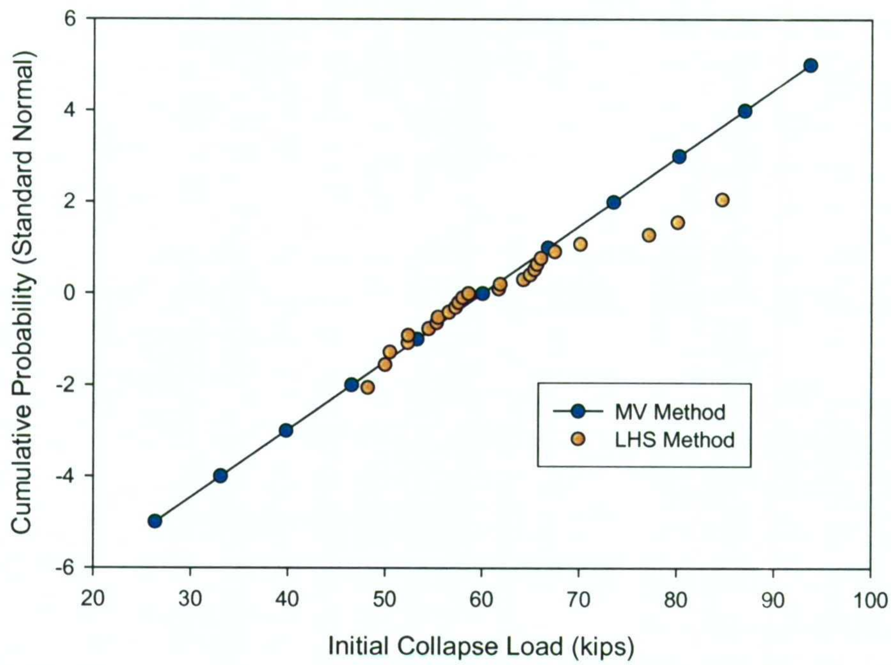


Figure 3: CDF of float collapse load.

Collapse Load Validation Testing

Traditional experiments are performed to improve fundamental understanding of physics, improve mathematical models, estimate values of model parameters or assess component or system performance. Data from these experiments are usually not adequate for model validation because of lack of control or documentation of some experimental parameters or inadequate measurement of specimen response.

In contrast, validation experiments are performed to generate high quality data for the purpose of validating a model. A validation test is a physical realization of an initial-boundary value problem. To qualify as a validation test, the specimen geometry, initial conditions, boundary conditions and material constitutive behavior must be prescribed accurately. The response of the test specimen to the loading must also be measured with high accuracy. Data collected during the test should include the applied loads, initial conditions, and boundary conditions, which might change throughout the test. Ideally, this will provide as many constraints as possible on the model inputs, requiring few if any assumptions on the part of the modeler. Generally, data from the archive literature are from traditional experiments and do not meet the requirement of validation testing. Therefore, it is usually necessary to perform experiments dedicated to model validation.

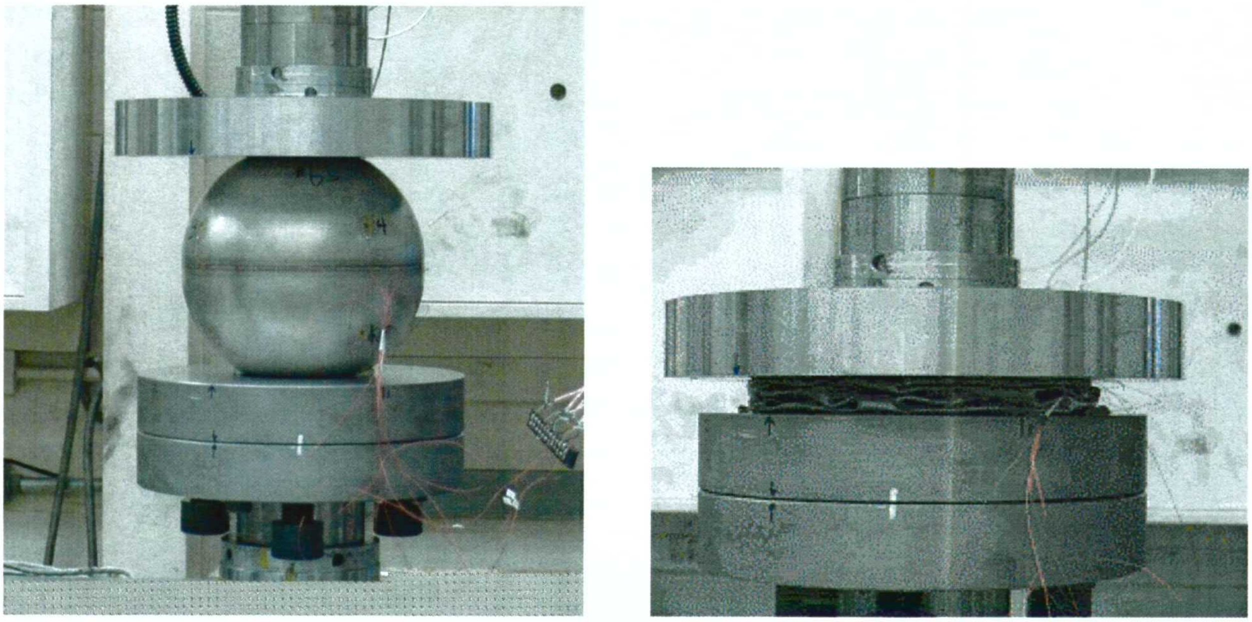
The experimental data are the standard for the model output. Therefore, it is essential to determine the accuracy and precision of the data from experiments. Uncertainty in the measured quantities should be estimated so that the predictions from the model can be credibly assessed. Uncertainty and error in experimental data include variability in test fixtures, installations, environmental conditions and measurements. Sources of non-determinism in as-built systems and structures include design tolerances, residual stresses imposed during construction and different methods of construction. It is unreasonable to expect a model to predict inaccurate or imprecise data.

To validate the uncertain collapse load prediction, 33 replicate collapse tests were performed at Southwest Research Institute (SwRI) in which the load was applied in one stroke (no load-unload cycles) and the peak load was not clipped. The floats tested were obtained from the original manufacturer as a separate purchase. A 200 kip load frame used to perform the testing, shown in Figure 4. Careful attention was given to ensuring that the load platens were rigid and remained aligned during the test. Complete details of the SwRI validation testing are given in Ref [6].

Figure 4: SwRI 200 kip load frame and float testing apparatus.

The load-displacement experimental data for the 33 floats are shown in Figure 6. The data is qualitatively similar to the LANL data with the exception that the initial peak load is not clipped and the load is applied in one stroke. As shown, the response up to about 5 in is similar from float to float. The response after 5 in, including the collapse load, is highly variable.

To look at the uncertainty in the observed collapse load from the SwRI experiments, the peak loads shown in Figure 6 were recorded from the 33 experiments. These 33 collapse loads were then used to generate an empirical CDF, which is shown in Figure 7 and labeled "Observed." The "predicted" CDF shown in Figure is the approximate "MV Method" CDF shown in Figure 3.



(a) (b)

Figure 5: Before (a) and after (b) pictures of a float being crushed.

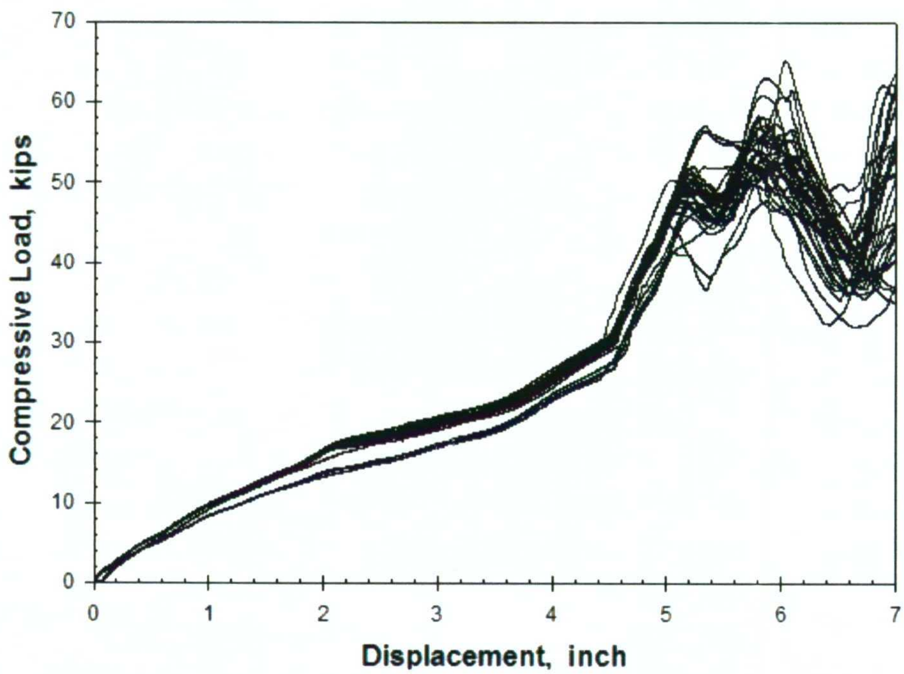


Figure 6: SwRI float test load-displacement data (33 tests).

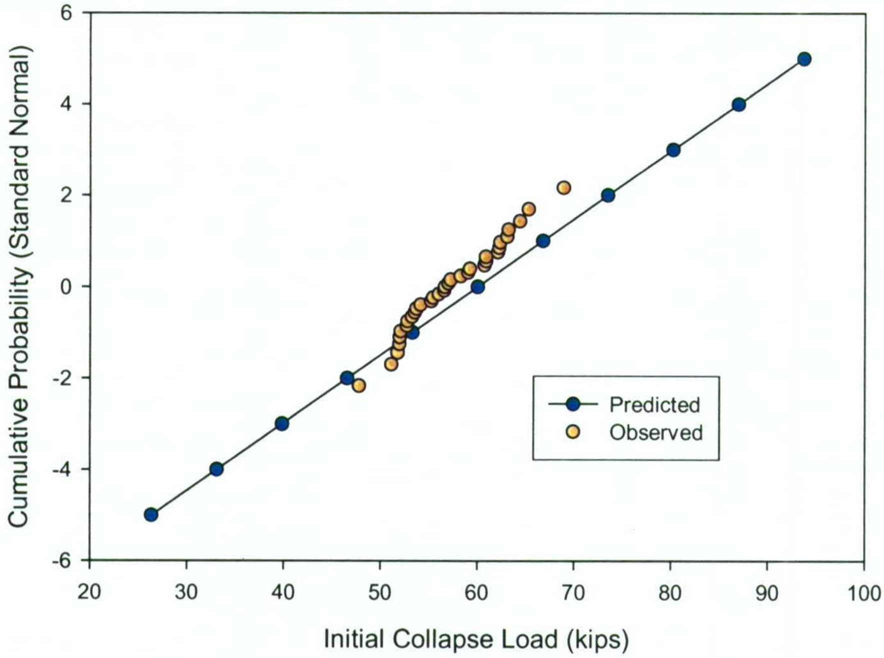


Figure 7: Predicted and observed CDF of the float collapse load.

Qualitatively, the predicted and observed CDF shown in Figure 7 are reasonably close. The observed CDF is approximate in that only 33 data points were used. The predicted CDF is approximate in that only a first-order probabilistic analysis was used to make the prediction. Consequently, comparisons between the two CDF should be limited to the mean value prediction (at 0 on the y-axis) and the standard deviation (slope of the CDF). These statistics are tabulated in Table 2.

Table 2: Measured and predicted float collapse load statistics.

	Mean (kips)	Standard Deviation (kips)	Coefficient of Variation
Predicted	60,022	6,732	11%
Observed	57,309	4,954	9%

As shown in Figure 7 and tabulated in Table 2, the predicted mean value is slightly higher than the observed mean value, and the predicted standard deviation is significantly higher than the observed standard deviation. The fact that the model predicts more uncertainty in the collapse load than what was observed is due to either the model input uncertainties being too large, or the physics of the float crush simulation not being sufficiently accurate. The coefficient of variation (COV) nondimensionalizes the comparison and is arguably a fairer comparison metric. As shown in Table 2, the model predicts only a 2% difference in COV than observed.

Summary

The predicted uncertainty was compared to the observed uncertainty in the collapse load of 33 spherical shells. The comparison metric was the cumulative distribution function (CDF) of the initial collapse load. The probabilistic shell collapse model considered uncertainties in material parameters (yield stress and modulus of elasticity) and geometry (radius and thickness). A random field model was used to simulate the spatial variability in both radius and thickness.

The difference between predicted and observed coefficient of variation was 2%. While this level of agreement is quite good, there are several aspects to the model development that still need to be addressed:

1. Improve the characterization of material properties. The cold-work process used to manufacture the shells creates variation in material properties as a function of location. This spatial variation as well as the inherent variation in material properties needs to be characterized and included in the probabilistic collapse model.
2. Validate the probabilistic model using advanced probabilistic methods.

Quantify the predictive accuracy of the collapse model. Based on the validation results (comparison to experimental data), the predictive accuracy of the model should be quantified. This will provide expected error bounds on the outputs of the model that reflect the level of confidence in the model.

References

1. NESSUS Version 7.55, Southwest Research Institute, July 2003.
2. Pepin, J.E. and B.H. Thacker, "Using Random Fields to Quantify the Geometric Shape Uncertainties of Spherical Marine Floats," IMAC-XXI: Conf. & Expo. on Structural Dynamics, Kissimmee, FL, Feb 2003.
3. Pepin, J.E., B.H. Thacker, E.A. Rodriguez and D.S. Riha, "A Probabilistic Analysis of a Nonlinear Structure Using Random Fields to Quantify Geometric Shape Uncertainties," Proc. AIAA/ASME/ASCE/AHS/ASC 42nd Structures, Structural Dynamics, and Materials (SDM) Conf., Denver, CO, 22-25 April 2002.
4. DYNA-3D User's Manual, "A Nonlinear, Explicit, Three-Dimensional Finite Element Code for Solid and Structural Mechanics," Lawrence Livermore National Laboratory, October 1999.
5. Haugen, E. B., Probabilistic Mechanical Design, Wiley, 1980.
6. McKeighan, P.C. & A.L. Veit, "Mechanical Testing of Spherical Marine Floats," SwRI Final Report, DV-FR-SwRI-MT-0001, Los Alamos National Laboratory, October 2003.

Corresponding Author: Jason E. Pepin
e-mail: jpepin@lanl.gov
Los Alamos National Laboratory
MS P946
Los Alamos, NM 87545
USA
Ph: (505) 665-9609
Fax: (505) 665-6333