Design and Analysis of a High-Performance Shipping Container for Large Payloads*

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DESIGN

The packaging designated the H1636A (Figure 1) is a high-performance packaging for large payloads. The H1636A is 50 in. in diameter and 113 in. in length and weighs approximately 4600 lb. when empty. The design objective was to meet 1996 proposed IAEA Type C criteria for air transport of large quantities of radioactive material (RAM). That is, the package should survive the standard Type B tests and more severe tests such as an impact onto an unyielding target at 280 ft/s and a 1-hour jet fuel fire.

The packaging consists of a large, double-walled, stainless steel outer drum filled with uniform density polyurethane foam. A stainless steel containment vessel (CV) with an inside diameter of 23 in. and a length of 78 in. carries the RAM. The CV has a nominal thickness of 0.375 in. and seals with two elastomeric O-rings. The lid of the CV is joined to the body with a unique closure called a tape joint. The tape joint utilizes interlocking features preloaded with wedges and can withstand significant deformation.

The CV is large enough to accept a variety of payloads, including damaged weapons. The packaging configuration of the payload depends on the specific type. However, in general, all payloads are surrounded by a significant amount of energy absorbing material to reduce the inertial loading in an accident.

ANALYSIS

To understand the physics of the package deformation and to refine the design, a finite element model was constructed to analyze high speed impacts.

Finite Element Model Development

Impact simulations were intended to provide estimates of strain levels in the containment vessel, the g (1g is the acceleration due to gravity) levels experienced by the mockup, and levels of container crush. While no attempt was made to accurately predict tearing of the

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outer drum or lid-bolt failure, the simulations would provide qualitative predictions of drum and lid integrity. The system was therefore modeled with sufficient detail to provide this information as economically as possible. The rationale behind various modeling assumptions and the resulting limitations are described in detail in the following subsections.

The impact simulations involve modeling nonlinear phenomena such as large deformations, nonlinear material response of metals and foams, and material self-contact. In addition, the combination of thin shell-like structures and regions of solid material in the H1636A necessitates use of both solid and shell-type elements. The three-dimensional transient solid dynamics code PRONTO (Taylor 1989) was selected because it is well suited to handle these challenges.

Simplifying Assumptions and Approximations in the Finite Element Model

Simplifying assumptions and approximations are used to limit model development time and cpu run time. The major assumptions and approximations are listed below.

- The CV is modeled with shells. The tape joint is modeled with equivalent thickness shells as are the axial stiffeners along the body of the CV.
- The foam was attached to the walls of the drum in the model. It is believed that the foam separates from the drum wall in an actual impact test so that the two materials are sliding upon one another. The foam-steel sliding contact was not modeled to save cpu run time. However, a test model (Figure 2(a)) was run to test this assumption, and it was found not to have a significant affect on the results.
- Only one drum lid was modeled, and the lid attachment screws were not modeled. The lid was "welded" to the outer drum in the model.
- The simulations assume the impact orientation is exact and that the target is perfectly rigid.
- The foam does not crack or experience damage. A significant amount of foam cracking was observed during disassembly of the test units.

Contact Surfaces

To allow the major components of the H1636A to move relative to one another, contact relations were defined. The resulting model (Figure 2(b)) allows the foam insert and containment vessel to move relative to the drum overpack and relative to one another (Heinstein et al. 1993). Within the containment vessel, the foam support closest to the lid can move relative to the vessel wall, and the mockup can move relative to both foam supports. The foam in the drum overpack was defined as a contact material to provide the self-contact capability required to allow it to fold up on itself during the extensive crushing experienced in the CG-over-corner impact.

Complete Model

The complete model included approximately 17,500 elements, with 13,200 8-noded hexagonal elements, and 4,300 4-noded quadrilateral shell elements. The model had a simulated weight of approximately 5000 lb. and required approximately 6 minutes of cpu time per millisecond of simulation. The finite element mesh is shown in Figure 2(b).

Material Properties

The stainless steel (containment vessel and drum) and the aluminum (load spreaders and mockup) were modeled as elastic/power law hardening materials using the EP POWER HARD constitutive model (Stone and Wellman 1990) implemented in PRONTO. The non-linear behavior of the rigid polyurethane foam was modeled with the Orthotropic Crush Model (Attaway 1992). Since the rigid polyurethane foam accounts for the majority of the system mass and energy-absorbing capacity, it was essential to validate the foam model.

A study was performed to correlate finite element predictions yielded by the Orthotropic Crush Model implemented in PRONTO with existing test data. The test data were obtained in unconfined uniaxial compression and hydrostatic compression tests of 20 lb foam (i.e., 20 lb per cubic foot) cube specimens by Lu (Lu et al. 1993).

Comparison data were obtained for uniaxial and hydrostatic compression. As illustrated in Figure 3, the numerical prediction agrees well with the experimental data.

COMPARISON OF SIMULATION RESULTS TO THE TEST DATA

As part of the pretest characterization of the H1636A design, axial, CG-over-corner, slap-down, and lateral simulations were performed at impact speeds of 44 ft/s, 250 ft/s, and 280 ft/s. Simulations were also performed to examine the effect of various design changes on the system response. The results and conclusions of the pre-test simulation study are documented by Slavin (1994). Instrumented tests were only performed at the 250 ft/s impact velocity. Therefore, the following discussion will only address the simulations corresponding to the 250 ft/s impact tests.

The impact orientations for the 250 ft/s tests were axial, CG-over-corner, and lateral. The tests were performed using rocket-driven pull-down. Separate test units were used, as the packages are significantly damaged in the impact. In the tests, the payload mockup was instrumented with fore and aft triaxial accelerometers, photometric records of the tests were taken, and the deformed packages were measured after the tests.

In the simulations, the plastic strain levels in the CV and the outer drum were monitored to qualitatively predict tearing or tape-joint failure, and the lid attachment was examined to determine if it would remain intact. Tearing was assumed to occur at 70 percent equivalent plastic strain in the 304 stainless steel (Rack and Knorovsky 1978). In addition, deformations of the unit were measured, and the mockup g-level history and the rebound velocity of the container were monitored. The simulations were run until the container rebounded.

A summary of some of the relevant comparison data for each test unit is listed in Table 1.

Table 1: Comparison of Simulation and Test Results

Orientation	Item	Simulation	Test
Axial	no tearing of drum or CV	✓	✓
	maximum axial drum deformation	12 in.	17 in.

Table 1: Comparison of Simulation and Test Results (Continued)

Orientation	Item	Simulation	Test
Axial	rebound velocity	50 ft/s	55 ft/s
	g levels	Figure 4	
cg-over-corner	upper mockup support heavily damaged	✓	✓
	outer drum flattened region	39 in.	42 in.
	rebound angular velocity	2.5 rev/s	3 rev/s
	g levels	Figure 5(top)	
side (lateral)	large CV deformations without tearing	✓	✓
	rebound velocity	40 ft/s	40 ft/s
	g levels	Figure 5(bottom)	

CONCLUSIONS

Again, it should be noted that the impact simulations were performed before the tests. Overall, the agreement between the simulation results and the test data is quite good. Nevertheless, it is instructive to examine and attempt to explain the differences between the simulations and the data. This can ultimately lead to refinements in future models, enabling them to more accurately capture system response.

In any impact simulation, there will be differences between the results and the test data caused by simplifying assumptions used in constructing the simulation model. For example, it is difficult to characterize the friction acting in a system, so either friction is neglected, or the friction coefficients used are simply a "best guess." In addition, simulation models typically assume perfect interfacial contact, where, in actual systems, random imperfections and gaps exist.

Because the H1636A is composed largely of foam, it is expected that the system response would be largely governed by the foam response. Accordingly, the foam model was carefully validated. Yet the inconsistent crush response observed in the axial and lateral simulations (i.e., underprediction in the axial, overprediction in the lateral) indicate that the foam model might not be capturing all of the phenomena encountered in the test. Underprediction of crush could indicate that the foam constitutive model is overpredicting the stiffness of damaged foam. In the impact, the foam could be weakened as a result of damage, which is not modeled in the simulations. Damage was not present in the characterization tests described by Lu (1993), and is therefore not reflected in the data used to calibrate the constitutive model. Examination of the crushed foam inside the outer drum revealed significant cracking in the lateral impact test unit. Overprediction of crush could be the result of strain-rate effects. Foam response is strain rate dependent, with the foam exhibiting greater strength with increased strain rate. The characterization tests were performed quasi-statically and therefore do not reflect this strengthening. Using dynamic crush properties in the simulations would indicate whether strain rate effects contribute to the observed differences.

The simulation model tended to overpredict the mockup g levels. Overprediction of foam stiffness could contribute to the high g levels. The predicted g levels could also be affected by the assumptions used in modeling the containment vessel with equivalent thickness shells. This could be examined by modeling the containment vessel in greater detail and comparing its response with the equivalent thickness shell model.

Finally, future models could include refinements to more closely approximate the observed response. Contact surfaces could be used to represent discrete foam sections that would be allowed to slide against one another, or damage models could be implemented. Also, future simulations could include the massive pulldown hardware welded to the external skin of the drum, more refined meshes, and ductile failure models to better predict the observed tearing.

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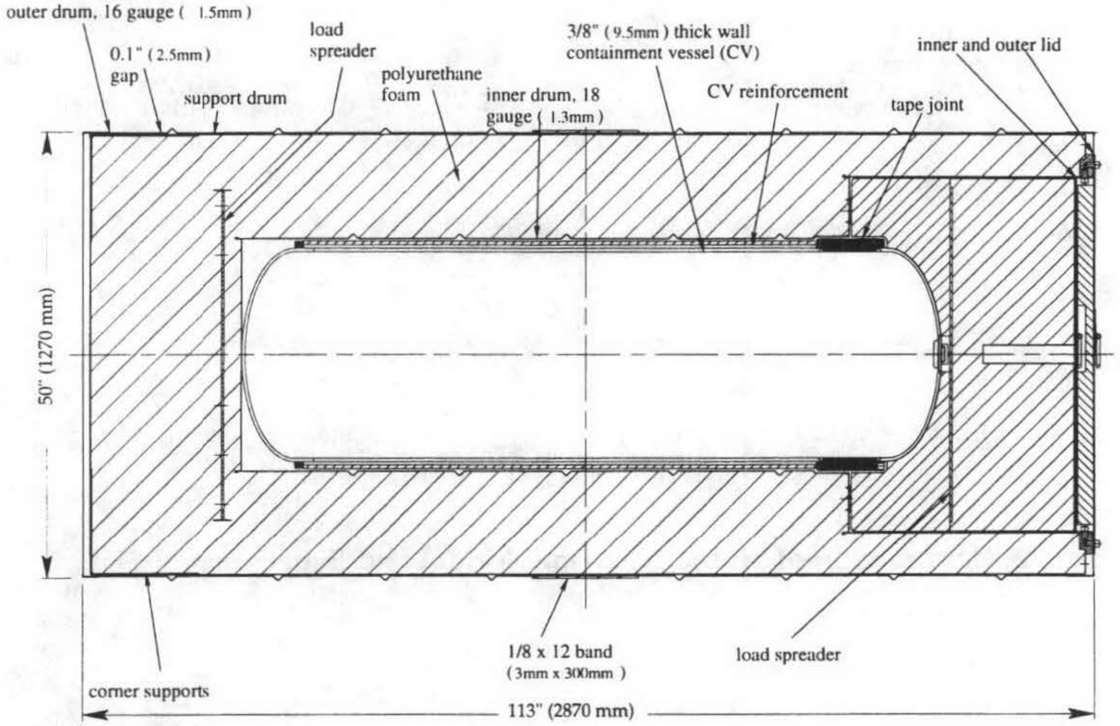

Figure 1. H1636A Packaging

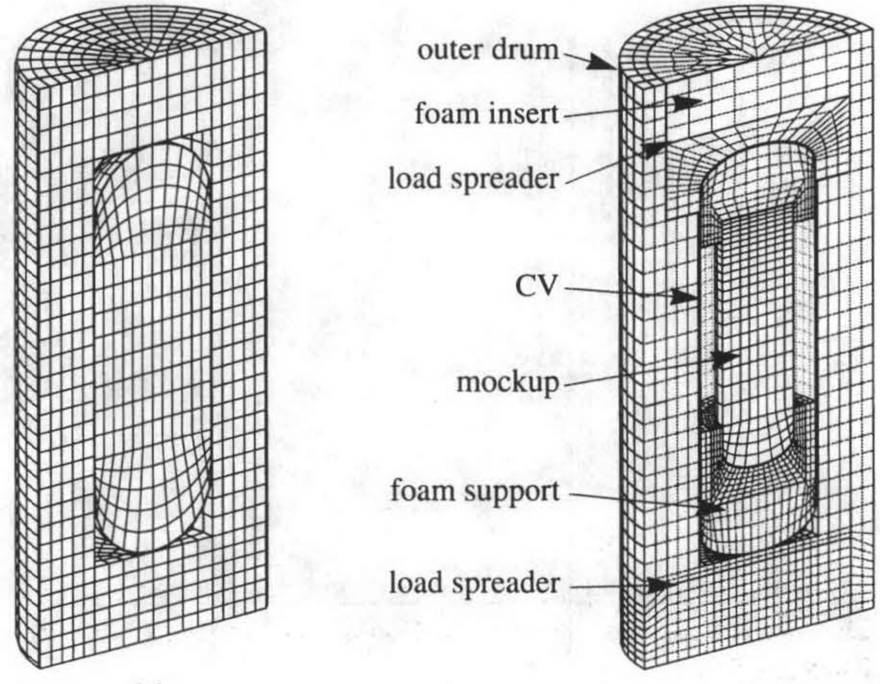

Figure 2. (a) Test Model and (b) Actual Model

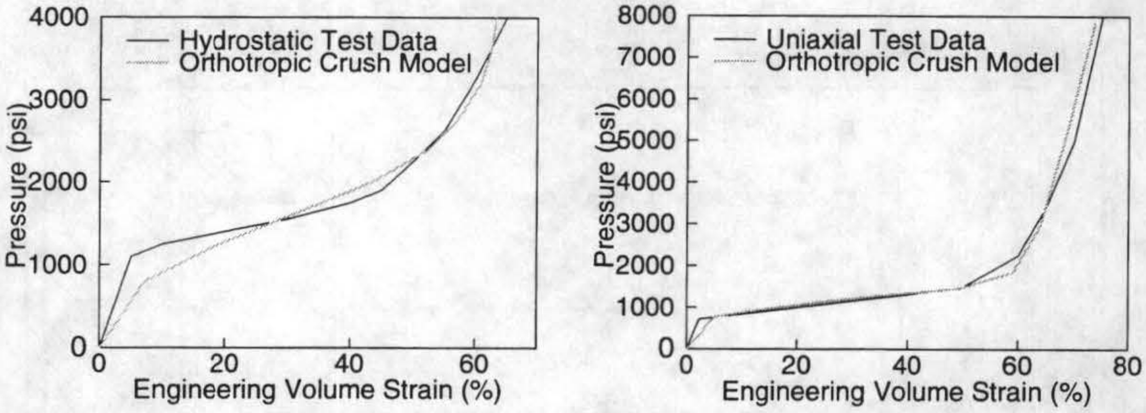

Figure 3. Comparison of Numerical Foam Model and Experimental Data

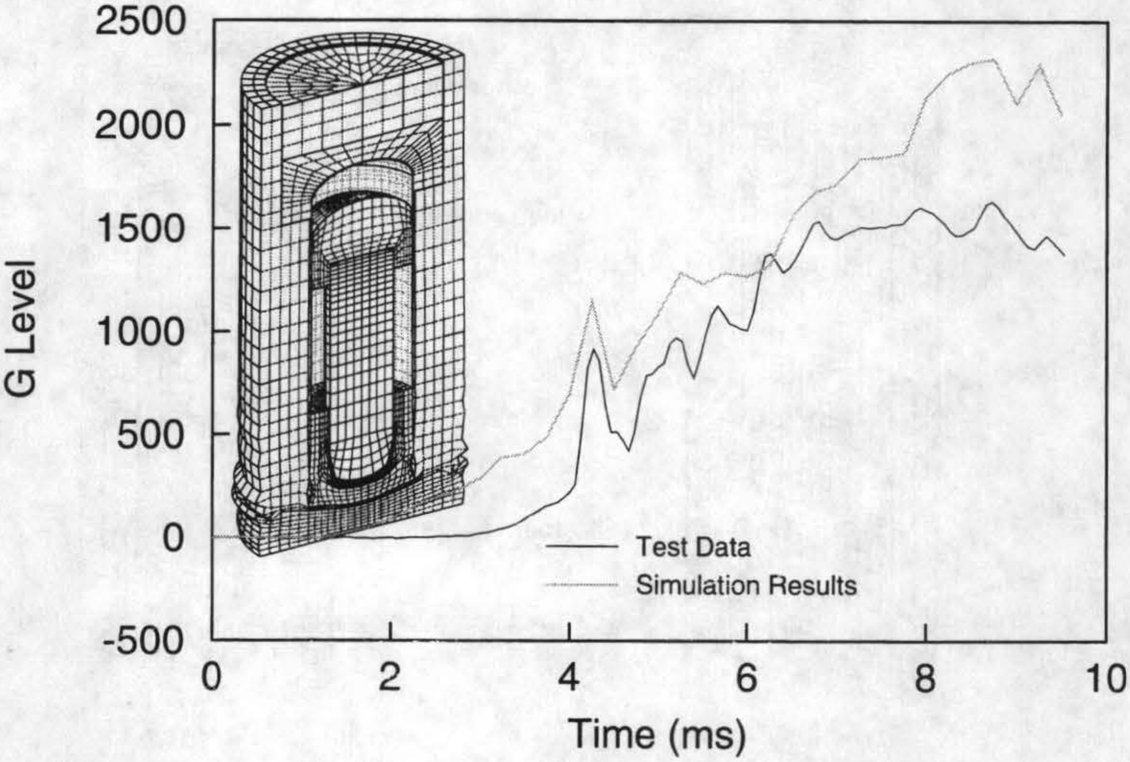

Figure 4. Axial Impact

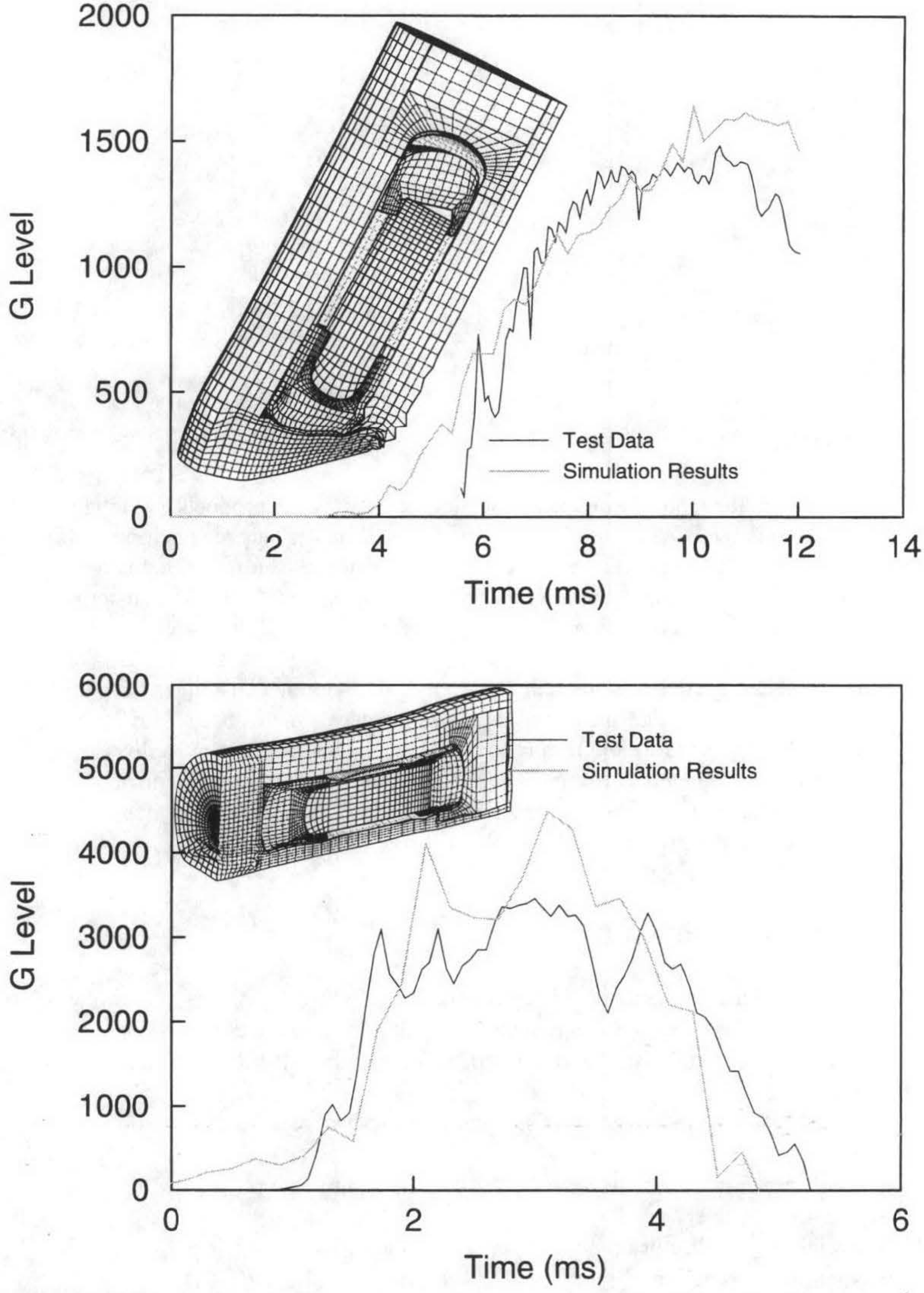

Figure 5. CG Over Corner Impact (top) and Lateral Impact (bottom)