Proceedings of the 17th International Symposium on the
Packaging and Transportation of Radioactive Materials
PATRAM 2013
August 18-23, 2013, San Francisco, CA, USA

VERIFICATION OF LS-DYNA MATERIALS USING SIMPLISTIC REPRESENTATIVE MODEL

A. K. Langston
TLI Engineering Services
1301 Gervais Street, Suite 450,
Columbia SC 29201 – USA

K. M. Martin
Global Nuclear Fuel
3901 Castle Hayne Road,
Wilmington, NC 28402 – USA

ABSTRACT

Verification and Validation is the largest area within software quality assurance activities. Verification provides evidence or substantiation, that a mathematical model is solved correctly by the computer code being assessed. Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. To successfully simulate a regulatory drop test, the mathematics (verification) and the physics (validation) of the model must provide an accurate representation of the actual package. As with all physics based computer codes, the accuracy of LS-DYNA is dependent on the material properties and proper use of the material models. A component study that demonstrates correct performance of a block, representative of honeycomb or another crushable material was performed and compared with laboratory and drop test data to provide reasonable assurance that the material model provides correct structural response. In summary, the simplified model was used to show that the input stress-strain curves resulted in accurate stress output. This paper provides procedures for verifying and validating the accuracy of LS-DYNA material models.

INTRODUCTION

During the evaluation of a packaging design to meet regulatory and non-regulatory testing requirements, it is necessary to develop reliable material models for use in codes such as LS-DYNA. The challenge is to obtain properties through laboratory and regulatory drop testing to verify and validate the analytical model used for design purposes. The process includes ensuring the properties match the physics of the problem, and the computer code properly interprets the input data.

RAJ-II PACKAGE

The package under investigation is the RAJ-II [Ref. 1]. The RAJ-II is a fresh fuel package designed to ship full length fuel assemblies and rods. The maximum gross shipping weight of a RAJ-II package is approximately 1,600 kg. As part of the licensing process, simulations were performed to investigate the performance of the package in drop orientations not originally evaluated during the drop testing program. Also of primary interest is the vibration performance of the package which is associated with road transport. Unlike package designs that ship spent fuel, isotopes, or waste materials, fresh fuel packages must be designed to provide protection for the components prior to operation. Therefore, the challenge is to design sufficient protection into the packaging to satisfy regulatory rigor and solve the classic packaging problem of maintaining the integrity of the payload during routine transport.

The RAJ-II packaging is comprised of an inner container and an outer container both made of stainless steel. Figure 1 shows a cutaway view of the packaging.

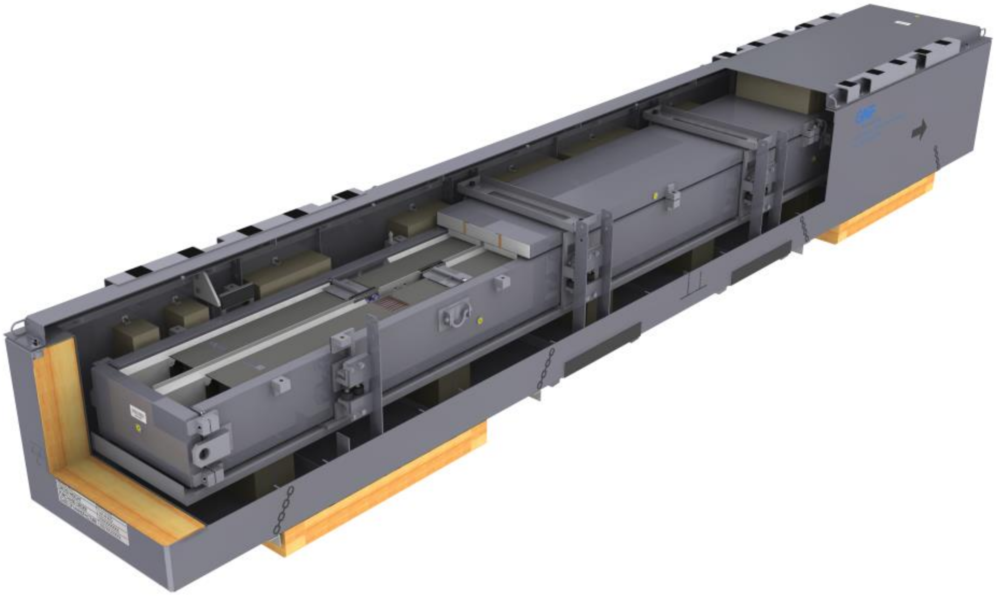


Figure 1. RAJ-II Package

Inner Container (IC)

The inner container is comprised of three parts: an inner container body, an inner container end lid (removable), and an inner container top lid (removable). These components are fastened together by bolts through tightening blocks. The inner container is a double-wall sheet metal structure with thermal insulation. Cushioning material is placed on the inside of the inner container for protection of each fuel assembly.

Outer Container (OC)

The outer container is comprised of three parts: a container body, a container lid, and inner container hold clamps fastened together with bolts. The outer container is made from metal angles that make the framework. Welded to the framework are bottom and side plates. Additionally, shock absorbers are attached to each end, top, bottom, and sides for absorbing energy due to a drop. The shock absorbers are of varying thicknesses and materials.

The outer container lid is comprised of a metal lid flange and a lid plate. The lid sling fittings are welded on the top surface of the outer container lid. The outer container lid has holes for bolts in its flange, so that it can be fastened to the outer container body.

Clamps, that are part of a support frame, restrain the inner container within the outer container. The support frame guides the inner container to the correct position and is fitted with the vibro-isolating mounts attached to the outer container frame designed to reduce sudden shocks and road vibration.

MATERIAL TESTING

To evaluate the packaging, it is necessary to obtain material properties through reliable published sources or laboratory testing. In many cases published data provided by material vendors does not adequately characterize the properties within the temperature range and strain-rates of concern. As a result, samples require testing at a material testing laboratory or on a material testing machine.

For this case, five samples of each material were cut with specific dimensions and sent to an independent testing laboratory. Force deflection curves were produced for each sample. To process the data, the curves for the five samples were averaged, and the force-deflection data was converted to stress-strain curves based on the sample cross-sectional area.

Honeycomb

The honeycomb used for impact protection was constructed with uniform density. Honeycomb properties were obtained by laboratory testing at –40°C, 21°C, and 77°C representing cold, ambient, and hot conditions [Ref. 2]. As described above, the force-deflection curves were obtained from the testing laboratory, averaged, and converted into equivalent stress-strain data. However, for honeycomb a further transformation was required to meet the input requirements of the LS-DYNA Material type 126. The strain component was converted to relative volume, where the relative volume was defined as the ratio of the current volume over the initial volume. The stress versus relative volume properties used in this example are shown in Table 1:

Table 1. Honeycomb Stress versus Relative Volume Properties

Relative Volume	Stress at 77°C		Stress at 21°C		Stress at -40°C	
	kPa	psi	kPa	psi	kPa	psi
0.140	1048	152	1386	201	1482	215
0.247	1000	145	1365	198	1365	198
0.435	910	132	1165	169	1193	173
0.718	676	98	531	77	993	144
1.000	462	67	276	40	427	62
1.100	462	67	276	40	427	62

Foam

Foam is used to line the inner container to provide vibration protection for the fuel bundles. Foam properties were obtained by laboratory testing at –40°C, 21°C, and 77°C representing cold, ambient, and hot conditions [Ref. 2]. The LS-DYNA Material type 063 model required the stress versus strain curve to be supplied. However, like the honeycomb model, further transformation of the foam was required. In this case, the strain for this model had to be input as volumetric strain, where the volumetric strain was defined as the ratio of the current length to the initial length minus one. The stress-strain properties used in this example are shown in Table 2:

Table 2. Foam Stress versus Volumetric Strain Properties

Volumetric Strain	Stress at 77°C		Stress at 21°C		Stress at -40°C	
	kPa	psi	kPa	psi	kPa	psi
0	0	0	0	0	0	0
0.014	21	3	62	9	76	11
0.042	48	7	90	13	117	17
0.071	76	11	124	18	159	23
0.099	138	20	200	29	241	35
0.134	379	55	579	84	627	91

Component Study

The first step in verifying the adequacy of the material properties was to perform a small-scale component study, which was used to show that the stress-strain properties were properly input and interpreted by the program. A simple crush model of a representative block of material, when compared with test data, provided reasonable assurance that the stress-strain properties are input and interpreted correctly. Figure 2 shows a simple model used to verify the material input. Figure 3 shows the verification results of the stress properties.

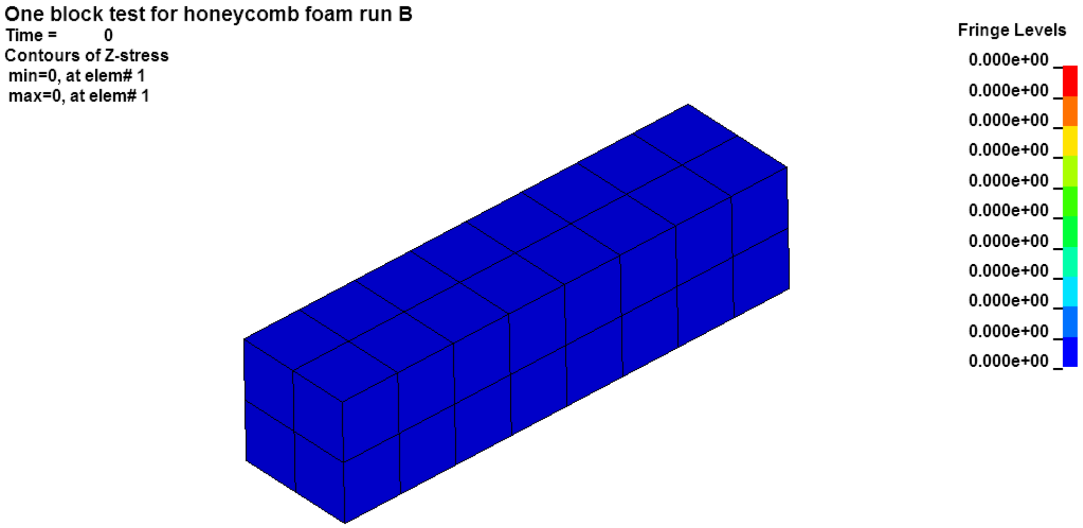


Figure 2. Simple Block Model used to Verify Material Input

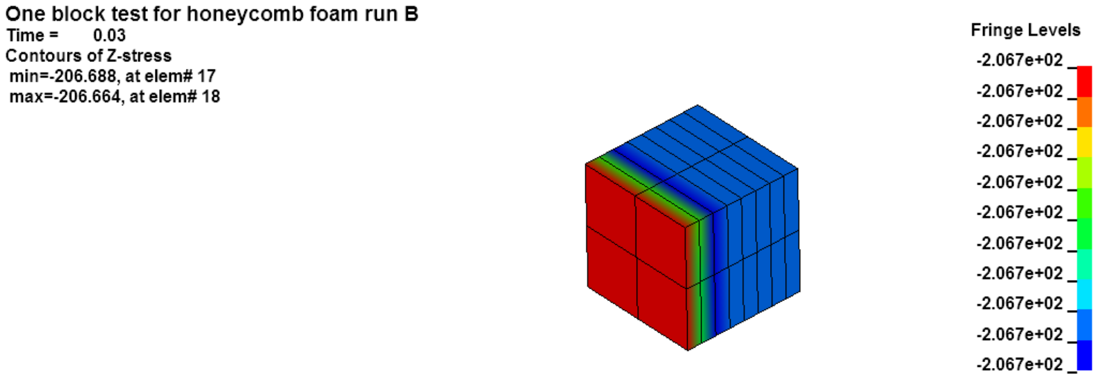


Figure 3. Simple Block Stress Results for Cushioning Material (psi)

To further verify the simple model was using the correct stress-strain input, the element strain and stress outputs were compared directly to the input curve. To verify that the correct input was used, the following steps were performed:

1. Update the simple model LS-DYNA input file with the stress-strain curve of interest.
2. Run the LS-DYNA model.
3. Open the d3plot file from the LS-PrePost window.

4. Identify an element to track results.
5. Select the element, save the strain as time-history.
6. Select the same element, save the stress as time-history.
7. Plot the input and output curves using the XYPLOT from the LS-PrePost window.
8. Scale the stress results as necessary. Stress results are negative because of compressive load.
9. Compare resulting curve with intended input.
10. If the input is correct, the input and output should match.

Using this technique, Figure 4 compares the input and output stress-strain curves.

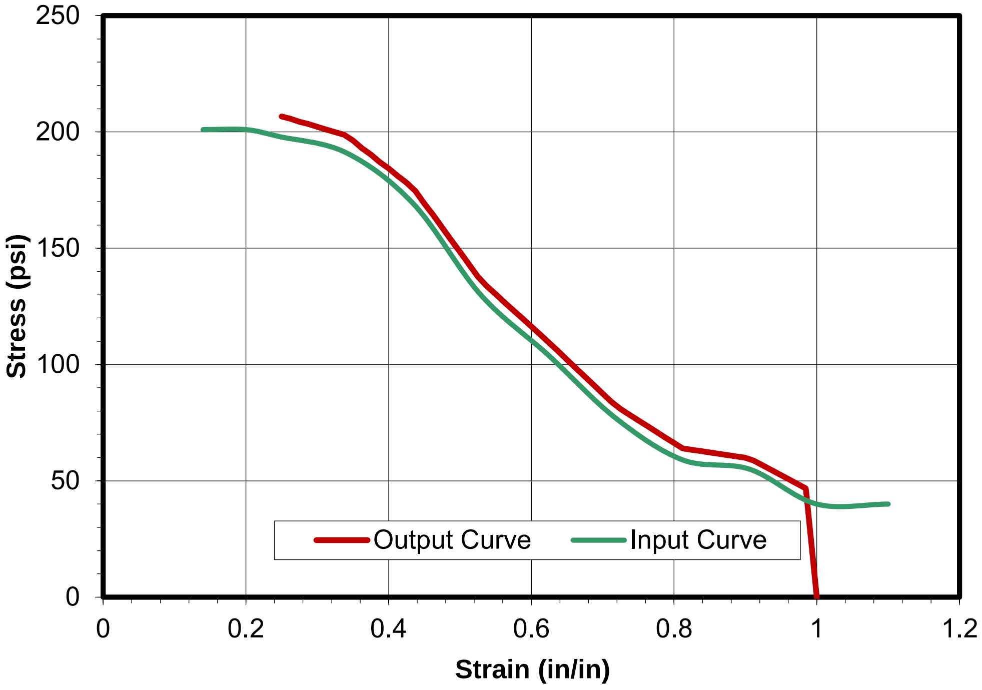


Figure 4. Simple Block Stress Results for Cushioning Material (psi)

Model Performance Study

Once the material models were verified, the material behaviors were further validated by applying the properties to simplified models of the package materials under evaluation. The purpose of this phase was to solve any problems that arose from having too fine or coarse a mesh. Figure 5 shows the RAJ-II inner container surrounded by the impact absorbing blocks. The model includes all of the crushable materials in the system and rigid payload mass, which simplifies the model to a mass spring system.

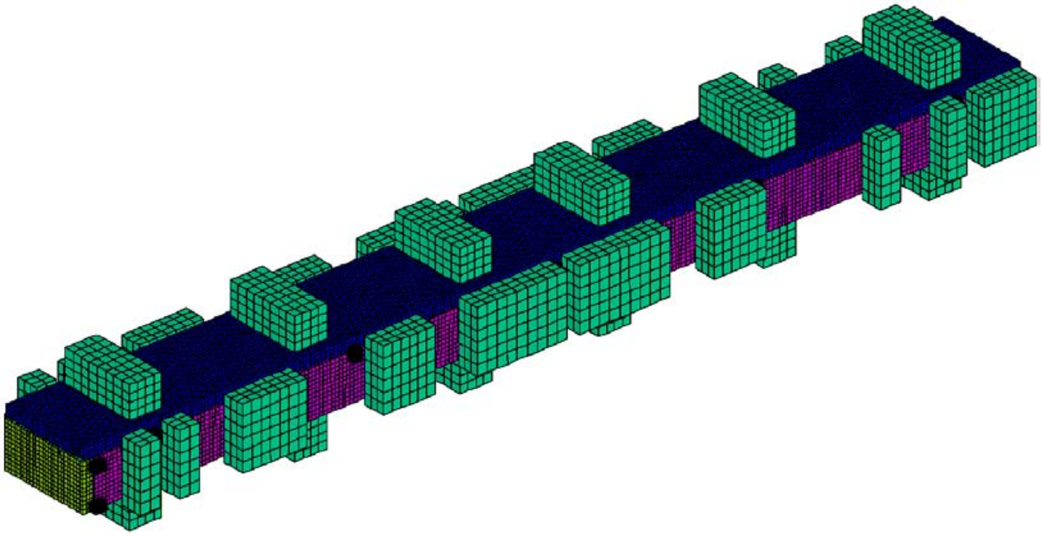


Figure 5. Simplified Finite Element Model to Evaluate Material Performance

LS-DYNA ANALYSIS

Once the material models and properties were verified, the LS-DYNA model was fully developed to determine the ability of the RAJ-II to meet the hypothetical accident conditions free-drop test requirements specified in IAEA TS-R-1 and to protect the fuel. Figure 6 shows the completed LS-DYNA model.

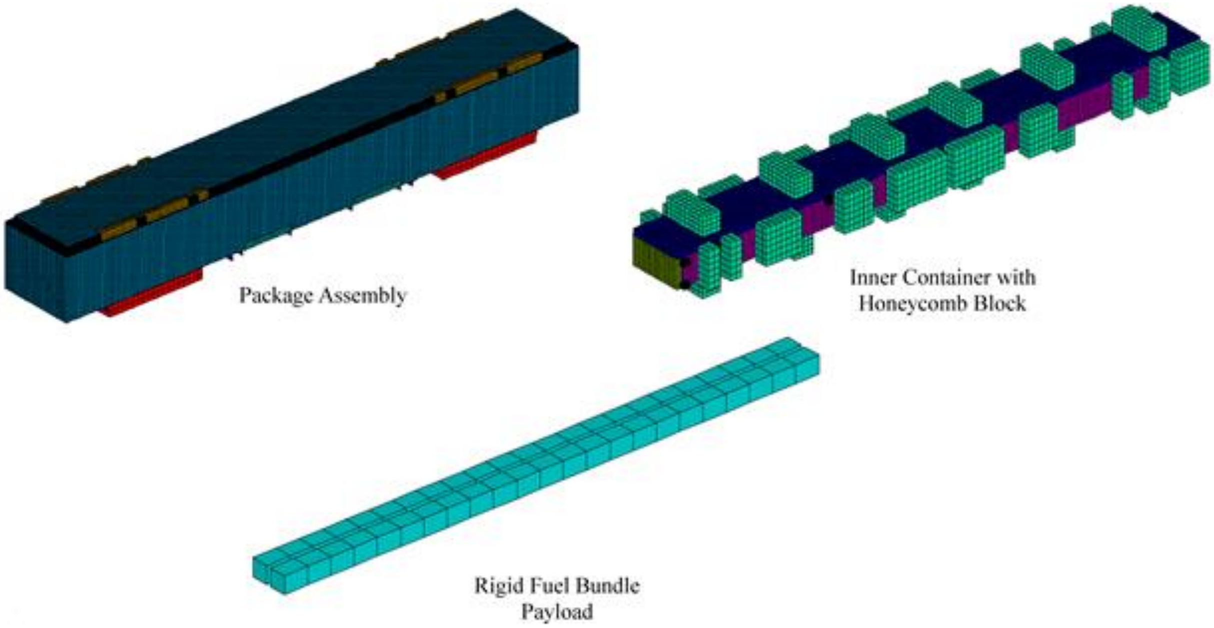
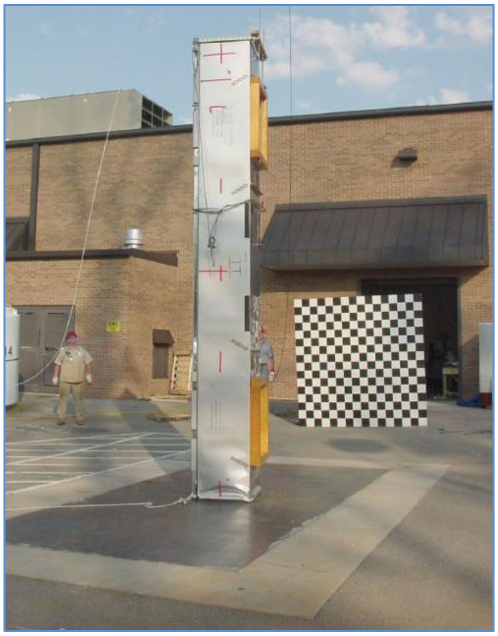


Figure 6. Complete RAJ-II FEA Model

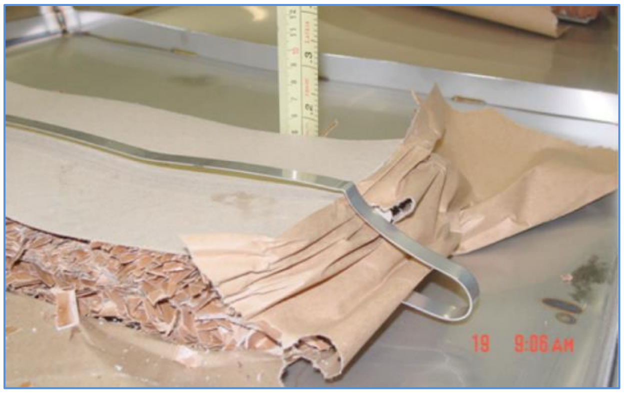
The impact study evaluated multiple drop conditions that intended to inflict maximum damage on the packaging: the 9-meter side and top drops simulated a transport accident in which the package is impacted on the flat side or top surfaces, slap-down/whiplash to determine whether an oblique angle may potentially produce high g loads during the secondary impact, and end drop.

REGULATORY TESTING



The RA series of containers were developed from a common design. The first generation design, known in the United States since the 1960's as the RA-3, consisted of a metal inner container and wooden outer container with honeycomb blocks and foam to line the inner container providing protection against impact and vibration. The equivalent Japanese and German designs were named the RAJ and RA-3D, respectively. The RA-3 is essentially the same design as the RAJ except it has a carbon steel inner container, no thermal insulation, and a wooden outer container. The RA-3D design is a similar design to the RA-3 with the exceptions of a stainless steel inner container, the addition of lifting trunnions, and latches used in place of bolts to secure the inner container lid. In the early 1990's, the Japanese developed the second-generation BWR container, RAJ-II, based on the lessons learned from the previous design including optimized impact protection.

Three independent testing programs were used to validate the RAJ-II design. In 1998, the RA-3D package was drop tested in Spain to show compliance with TS-R-1 by GE, ENUSA, BAM and BfS [Ref. 3]. The RA-3D provides an ideal benchmark comparison to the RAJ-II, because dimensionally the RA-3D is almost identical to the RAJ-II in length, width, and height. In comparing impact accelerations, these two designs showed good agreement. However, the peak acceleration of the RA-3D is higher than that of the RAJ-II because of increased honeycomb surface area during the initial impact and decreased honeycomb height, which was confirmed by hand calculations. Since the RAJ-II and RA-3D are of similar construction and transport the same fuel designs, the impact duration and acceleration peaks align with analysis predictions and provide a valuable benchmark for bounding impact accelerations.



Testing of the RAJ-II in Japan occurred independently of other testing programs to comply with Japanese regulatory requirements. The design underwent both normal conditions of transport and hypothetical accident conditions testing, which resulted in obtaining a Type AF-96 certificate of compliance in Japan.

The U.S.A. testing was conducted in 2003. Testing was performed at the National Transportation Research Center in Oak Ridge, Tennessee. Two certified test units were tested to evaluate the performance of the package during 9-meter slap-down, 1-meter puncture, and 9-meter end drop. GNF-A obtained a Type B(U)F-96 certificate of compliance in the U.S.A for the RAJ-II.

COMPARISON OF REGULATORY TESTS AND LS-DYNA RESULTS

The results of three independent testing programs were used to provide valuable benchmarks for the LS-DYNA model. Accelerometer data was not available for the side drop case during either of the two

RAJ-II testing programs; therefore, the best comparison for the RAJ-II side drop case was the data available from the BfS test program for the RA-3D. As Figure 7 shows, the LS-DYNA analysis properly captured the response of the initial impact and subsequent secondary responses of the fuel, as the crushable materials in the inner container deform and flex.

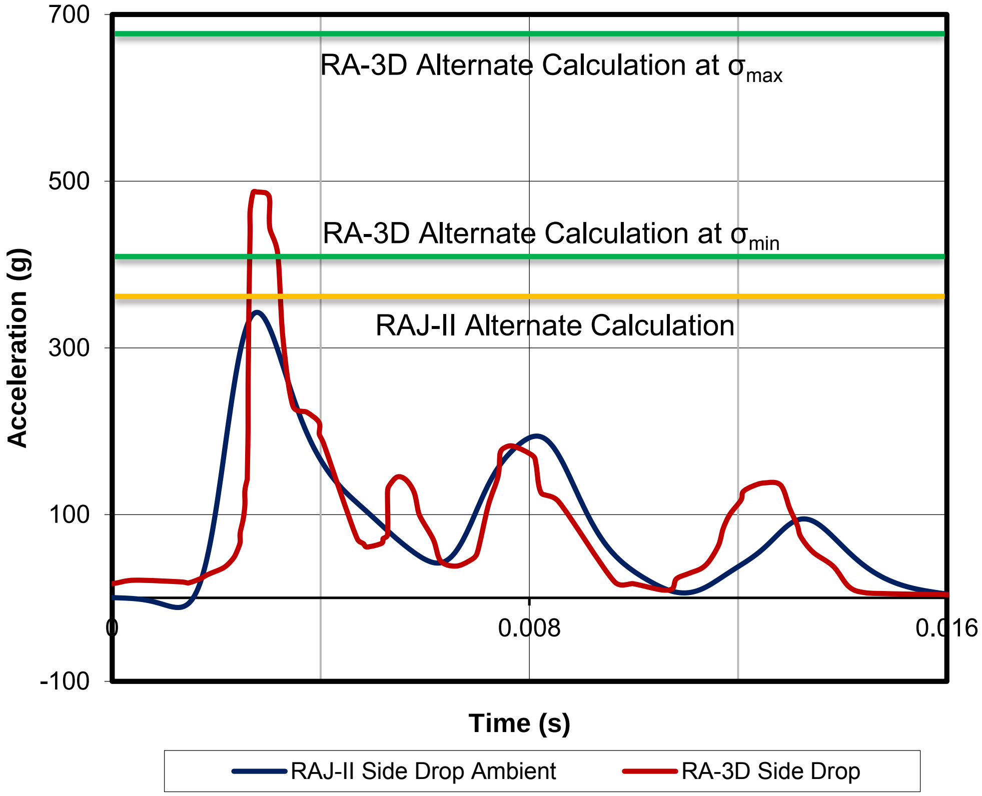


Figure 7. Comparison of RA-3D Side Drop Test (Red), RAJ-II LS-DYNA Side Drop Ambient (Blue), and Ambient Alternate Calculation Accelerations (Green and Orange)

LS-DYNA RESULTS VERIFICATION WITH ENERGY BALANCE CALCULATIONS

In order to verify the adequacy of the RAJ-II side drop LS-DYNA results, energy balance calculations were used to verification impact acceleration projections. To benchmark the approach, a model already shown to agree with measured test impact accelerations was first evaluated. The model chosen was the top drop orientation, which is a flat drop onto the same type of cushioning material as the side drop. However, in order to begin benchmarking the top drop case, honeycomb properties needed to be established for a different material thickness than tested and a dynamic load factor needed to be selected.

The testing of the honeycomb material properties included a single thickness which varied from other honeycomb thicknesses used in the package design. Thus, when using first principle calculations to bound LS-DYNA analysis results, the peak compressive strength of the honeycomb had to be scaled for those package orientations engaging untested honeycomb thicknesses. The following steps were taken to scale the honeycomb compressed height, as well as the peak compressive strength. The compressed heights of various honeycomb thicknesses were assumed to have a linear relationship, resulting in the following equation:

$$L_{compressed,test} \times \frac{L_{uncompressed,actual}}{L_{uncompressed,test}} = L_{compressed,actual}$$

The peak compressive strengths of the various honeycomb thicknesses were scaled using the following approach.

$$\text{Since, } \sigma_{critical} = \frac{\pi^2 EI}{AL^2} \Rightarrow \sigma_{critical,test} \times \frac{L_{uncompressed,test}{}^2}{L_{uncompressed,actual}{}^2} = \sigma_{critical,actual}$$

Once material properties were established, a dynamic load factor of 2 was first applied in confirmatory energy balance calculations. A factor of 2 was used for sudden, direct impact against cushioning material with high peak stress. As shown in Figure 8, the results showed good comparison for the RAJ-II top impact.

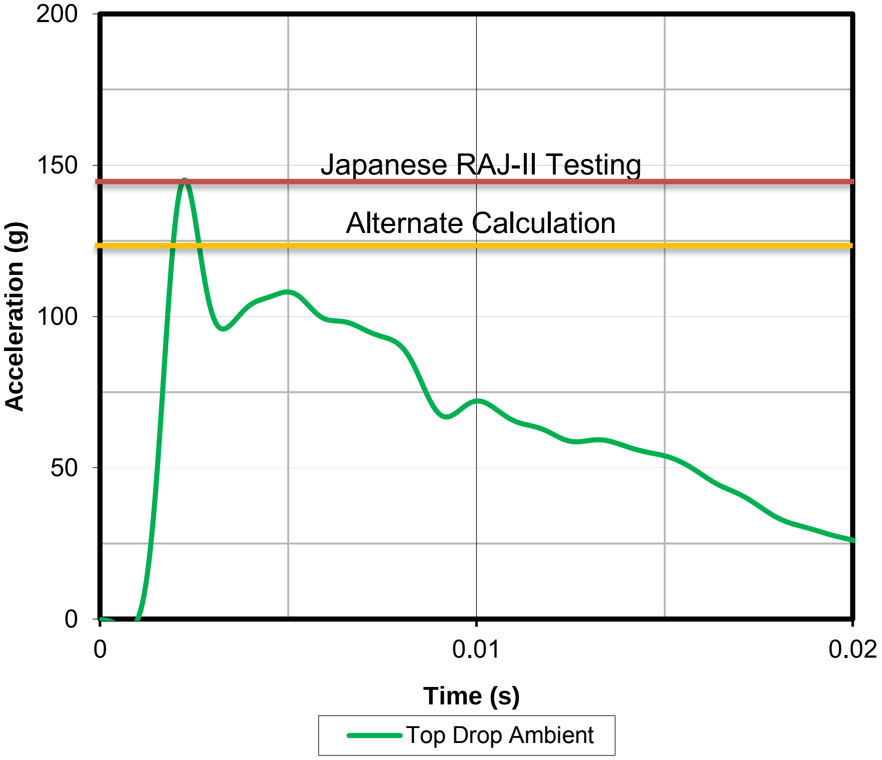


Figure 8. Comparison of RAJ-II LS-DYNA Top Drop Ambient Results (Green), Japanese RAJ-II End Drop Test (Red), and Ambient Alternate Calculation (Orange)

In order to validate the use of the dynamic load factor of 2, it was applied to an impact case with similar conditions, the side drop. Both impacts are flat and engage the same cushioning material, with high peak compressive strength. The RAJ-II and the RA-3D side drops were both assessed in this manner. The RAJ-II calculation was performed at the experimentally determined compressive strength, while the RA-3D calculations were performed at the minimum and maximum compressive strengths provided on the engineering drawing to bound results. Both again showed good comparison; see Figure 7.

Once the adequacy of the LS-DYNA model had been demonstrated, the model was used to benchmark dynamic load factors for other impact orientations for future engineering use. It was determined that the dynamic load factor depends on:

1. The type of crushable material engaged during impact
2. The orientation of the crushable material versus impact plan

The following basis was developed for the dynamic load factors and found to be a valid approach for the RAJ-II package.

Table 4. Dynamic Load Factors

Factor	Conditions	Drop Orientation
2.00	Sudden, direct impact against cushioning material with high peak stress	Side (Fig. 7), Top (Fig. 8)
1.50	Sudden, oblique impact against cushioning material with high peak stress	Slap Down (Fig. 10)
1.33	Sudden, oblique impact against surfaces of various cushioning materials	Corner (Fig. 9)
1.33	Sudden, direct impact against cushioning material with approximately linear stress-strain distribution	End (Fig. 11)

Figures 9 and 10 show application of Table 4 dynamic load factors for slap down and corner drop orientations. Figure 11 represents the end drop of the package, and the crushing of the wood blocks used for impact protection located at the end of the container. Benchmarking of the wood properties was accomplished by taking measurements from the wood post impact and comparing to the LS-DYNA predicted crush height. Evaluation of the CTU showed that a maximum crush of 2 inches occurs under the point of impact, which agreed with the LS-DYNA results.

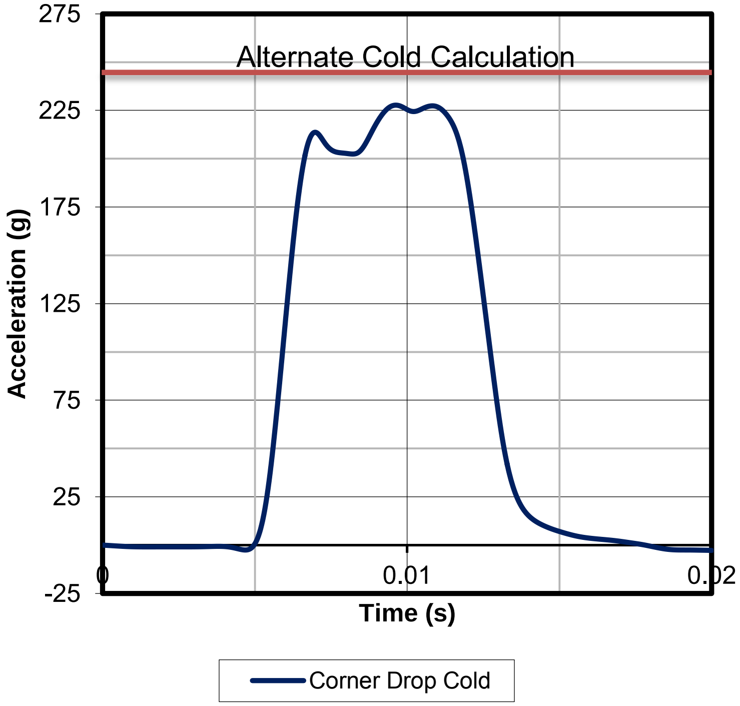


Figure 9. Comparison of Cold LS-DYNA Corner Drop Results (Blue) and Cold Alternate Calculation (Red)

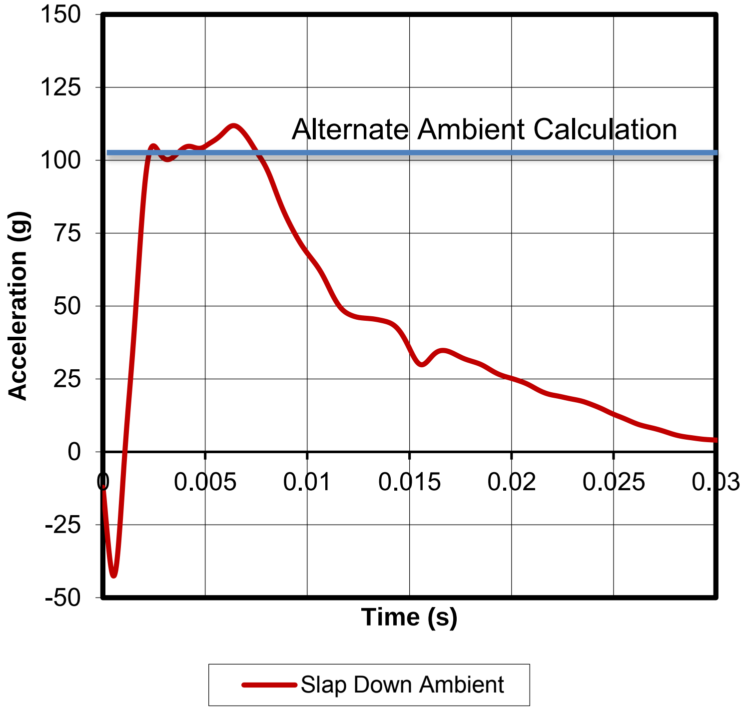


Figure 10. Comparison of Ambient LS-DYNA Slap Down Drop Results (Red) and Ambient Alternate Calculation (Blue)

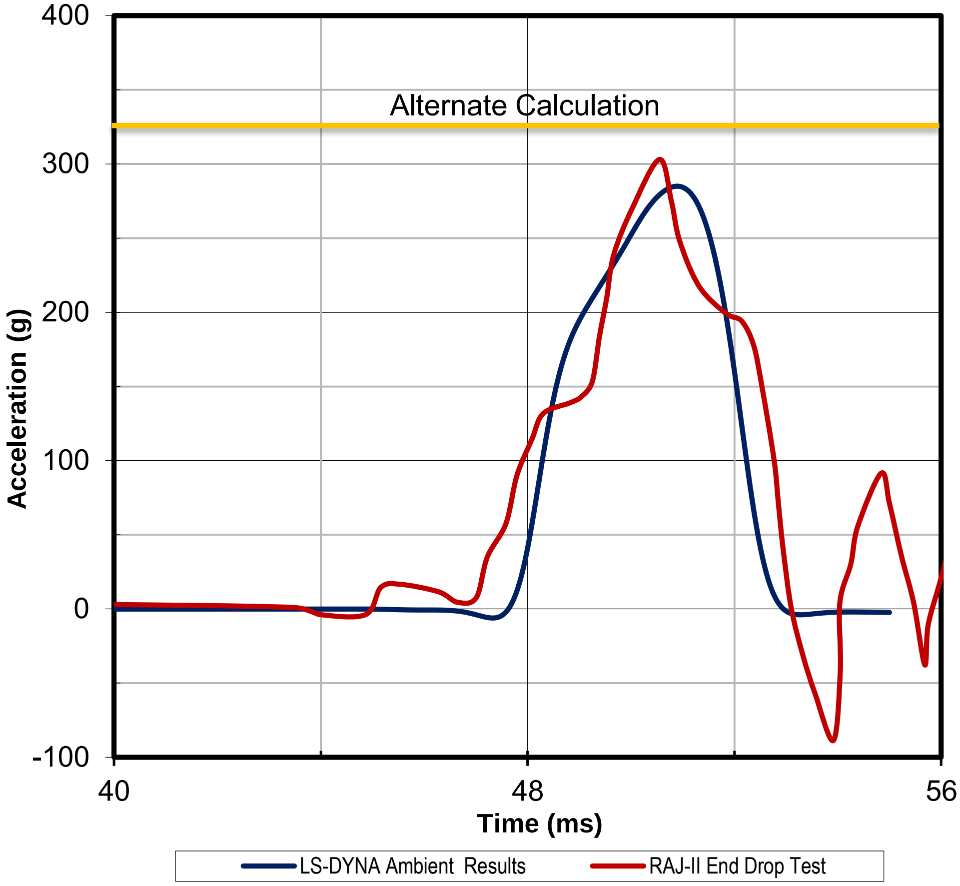


Figure 11. Comparison of Ambient Japanese RAJ-II End Drop (Red), Ambient LS-DYNA Results (Blue), and Ambient Alternate Calculation (Orange)

CONCLUSIONS

During the packaging design process, it is critical to understand the performance of the crushable materials. As a result, it is necessary to perform laboratory testing to obtain crush data for the specific range of conditions unique to the package design. This evaluation shows that the combination of material testing, comparison to regulatory test results, and the use of classic hand calculations provides sufficient assurance that the FEA model provides dependable results, which can be used to predict the performance of the packaging under various conditions without additional physical drop testing.

REFERENCES

1. "Safety Analysis Report for the Global Nuclear Fuel (GNF) RAJ-II," USA/9309/B(U)F-96, Docket Number 71-9309, Global Nuclear Fuel-Americas, Wilmington, NC, USA.
2. Honeycomb and Ethafoam Compression Test Results, Test Report GEN015-08-05-59922-1, Stork Herron Testing Laboratories, 5404 E. Schaaf Road, Cleveland, OH 44131 USA.
3. P. P. Millan (ENUSA), C. Vaughan (GNF), B. Gogolin (BAM), "Drop Test for the Licensing of the RA-3D Package in the Transport of BWR Fresh Fuel Assemblies," Proceedings from The International Symposium on Packaging and Transportation of Radioactive Materials (PATRAM), Chicago, Illinois, USA (2001).