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Verification of LS-DYNA Finite Element Impact Analysis by Comparison to Test Data and Classic First Principle Calculations

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ABSTRACT

The Global Nuclear Fuel (GNF) RAJ-II fuel package for transportation of BWR fuel bundles is a second-generation, Type B(F), all stainless steel package designed to replace the older wooden/steel package design. The RAJ-II licensing is a collaborative effort between GNF, Westinghouse, and AREVA. During recent licensing activities in the EU, questions regarding the performance of the package during regulatory impact events were addressed. In order to evaluate the effectiveness of the RAJ-II BWR fuel container during a variety of impact conditions and orientations, a comprehensive LS-DYNA model was developed. To benchmark the model, analytical results were compared to drop test data from the RAJ-II development program and similar first generation designs. Verification of the LS-DYNA analysis was performed using first principle calculations. Because the impact absorbing materials that protect the RAJ-II are comprised of simple shapes and materials that are well characterized, the classic calculations successfully bounded the LS-DYNA and test results. This study has shown that combining finite element analysis, drop test data, and classic first principle calculations is an effective approach for evaluating and optimizing package design.

INTRODUCTION

During licensing review, the French Radiation Protection and Nuclear Safety Institute, Institut de Radioprotection et de Sûreté Nucléaire (IRSN), and Nuclear Safety Authority, Autorité de Sûreté Nucléaire (ASN), requested additional information concerning the impact performance of the RAJ-II BWR fuel package [Ref. 1]. Specifically, IRSN/ASN requested further evaluation of the hypothetical accident impact performance of the package to determine the maximum acceleration of the fuel bundles under various drop conditions including flat-side/top drops and slap-down/whiplash.

EVALUATION

This evaluation is a sensitivity study 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 protect the fuel bundles [Ref. 2]. This paper evaluates three drop conditions that intend to inflict maximum damage on the packaging. The 9-meter side/top drops simulate a transport accident in which the package is impacted on the flat side or top surfaces. The slap-down/whiplash is unique to long packages where the corner or edge of the package impacts the target surface at an angle potentially producing high g-loads during the secondary impact due to a whipping action generated by the force of the first impact.

LS-DYNA Finite Element Model

In order to evaluate the effectiveness of the RAJ-II BWR fuel container during a variety of impact conditions and orientations, a comprehensive LS-DYNA model was developed. LS-DYNA is a commercially available general-purpose multiphysics finite element analysis (FEA) program using explicit time integration.

The initial solid model of the RAJ-II is developed using Autodesk Inventor. The Inventor model is developed from the RAJ-II fabrication drawings. The model is constructed of solid objects that represent the crushable materials and surfaces for most steel components. Surfaces are two-dimensional objects that represent the center plane of the original solid surface. Figure 1 shows the Inventor solid model.

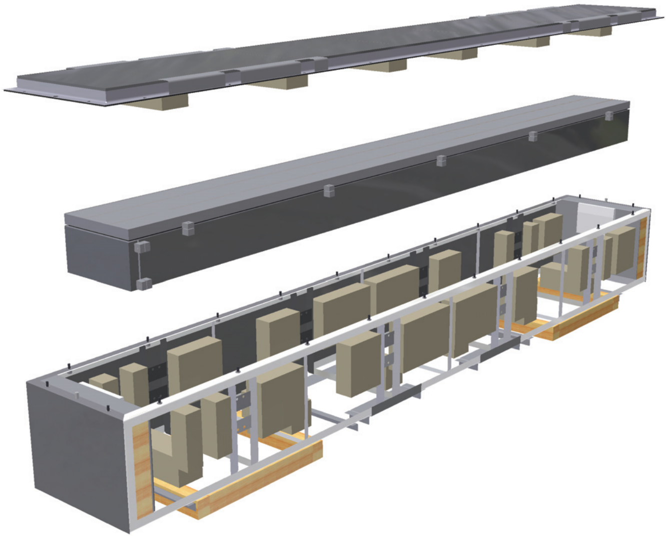
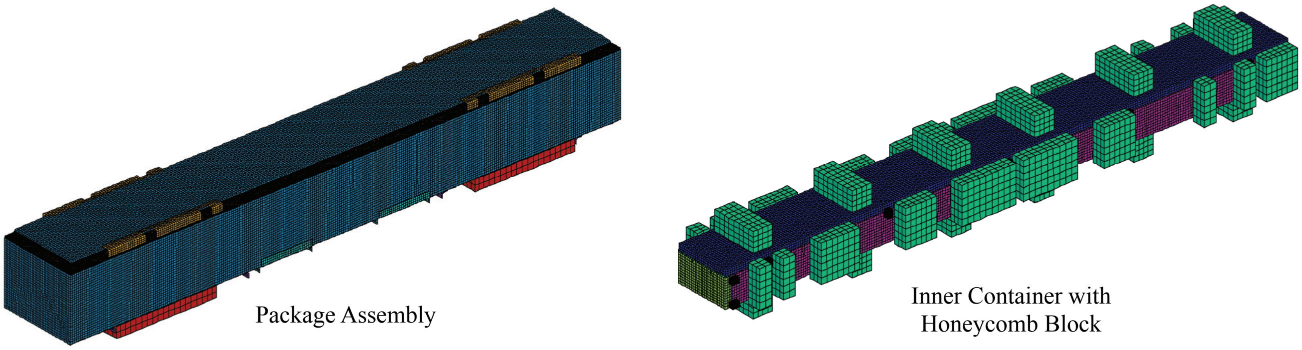


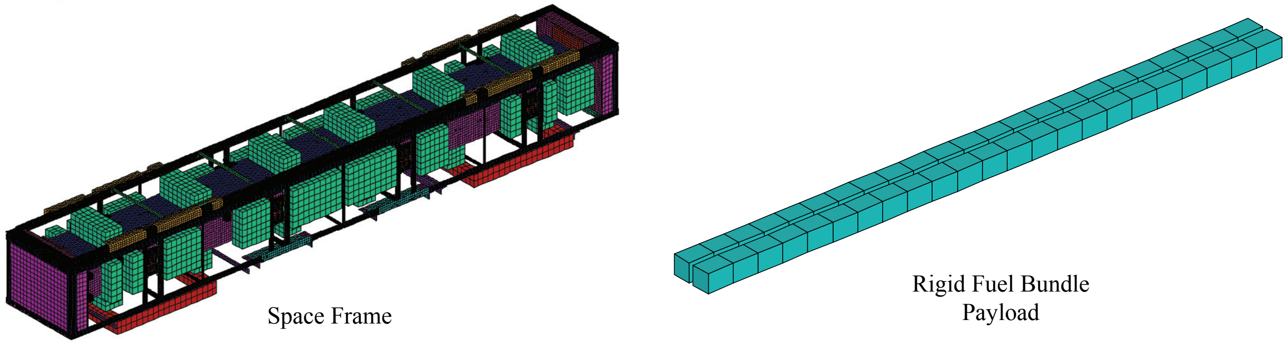
Figure 1 – RAJ-II Solid Model

The finite element model is generated by importing the Inventor solid model into ANSYS Workbench and meshed using the Workbench meshing tools. Once meshed in Workbench, an ANSYS classic input file is created and opened in ANSYS Mechanical using the ANSYS LS-DYNA PrepPost license. Once the finite element model is completed, the ANSYS 'EDWRITE' command is issued to save the nodes and elements into the standard LS-DYNA keyword file format. The resulting LS-DYNA model is imported into the LSTC LS-PREPOST, which is launched from the LS-DYNA manager to ensure elements are translated from ANSYS properly. The keyword file is then edited to include control cards, database cards, material cards, and boundary condition cards. Figure 2 shows the fully assembled model and each individual part.



Package Assembly

Inner Container with
Honeycomb Block



Space Frame

Rigid Fuel Bundle
Payload

Figure 2 – RAJ-II FEA Model

The materials properties in the following section are based on laboratory test results and open literature. To ensure accuracy of the material model, the top drop analysis results are benchmarked with the RAJ-III (RAJ-II plus loose rod container) top drop test [Ref. 1]. For the Honeycomb, the instantaneous modulus of elasticity, E, is increased until the peak acceleration equals 145g, as shown in Figure 3.

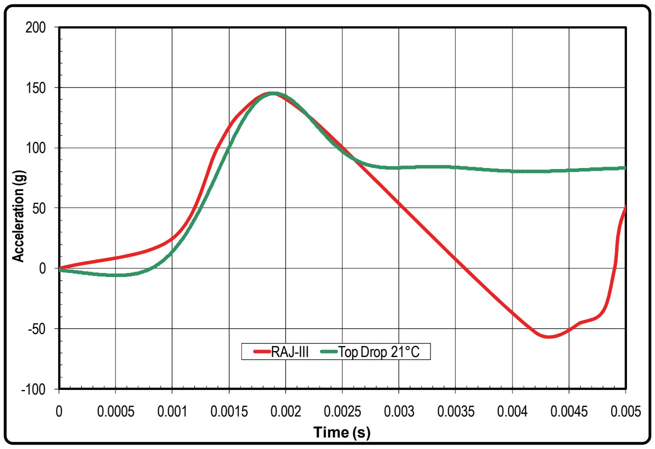


Figure 3 – Benchmark of LS-DYNA with Drop Test Results

Material Properties

The structural components of the RAJ-II are constructed of 304 stainless steel, Paper Honeycomb, Balsa, Hemlock, flexible polyurethane foams, and Aluminum Silicate. General properties are provided in the RAJ-II SAR.

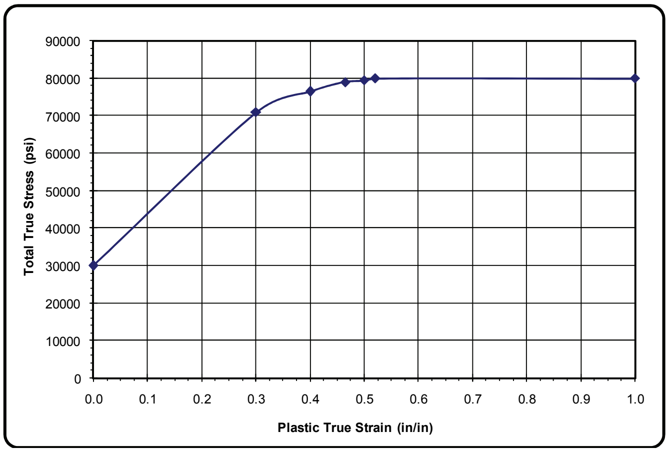


Figure 4 – True Stress versus True Strain for 304 SS

Stainless Steel: Steel components are modeled with 304 stainless steel properties as an elasto-plastic material using the LS-DYNA material model *MAT PIECEWISE LINEAR PLASTICITY [Ref. 3]. The true stress-strain curve is given in Figure 4.

Paper Honeycomb: The paper honeycomb used for impact protection is constructed of resin impregnated kraft paper of uniform density. Honeycomb properties were obtained by laboratory testing at –40°C, 21°C, and 77°C representing cold, ambient, and hot conditions. The honeycomb is modeled using the LS-DYNA material *MAT_HONEYCOMB. The stress-strain properties for honeycomb are provided in Figure 5.

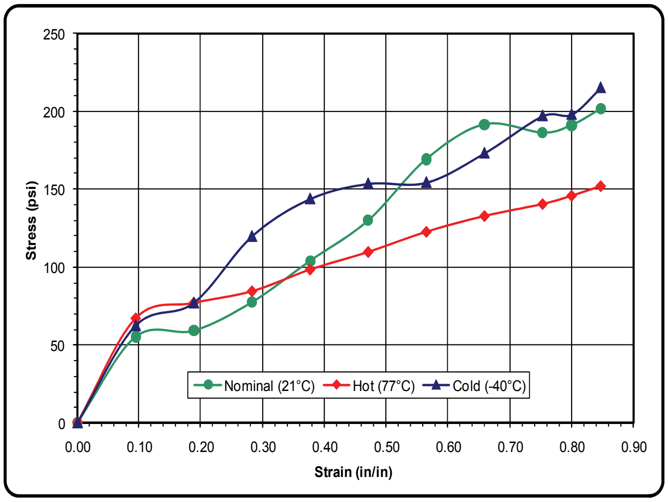


Figure 5 – Honeycomb Engineering Stress-Strain Properties

Ethafoam: The Ethafoam is used to line the inner container to provide vibration protection for the fuel bundles. Ethafoam properties were obtained by laboratory testing at -40°C, 21°C, and 77°C representing cold, ambient, and hot conditions. The Ethafoam is modeled using the LS-DYNA material *MAT CRUSHABLE FOAM. The stress-strain properties are provided in Figure 6.

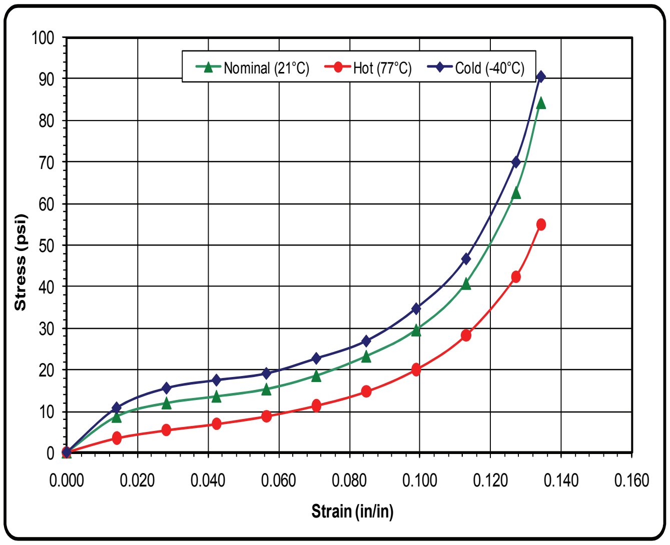


Figure 6 – Ethafoam Engineering Stress-Strain Properties

Fuel Bundles: The fuel bundles are modeled as rigid bodies to ensure no energy is dissipated by the contents. The fuel bundles are modeled using the LS-DYNA material *MAT_RIGID.

The bundle mass is based upon the range of standard designs shipped in the RAJ-II. Analyzed fuel bundle weights are based on actual design weights.

Boundary Conditions

The LS-DYNA command *RIGIDWALL GEOMETRIC FLAT is used to define the infinitely rigid impact plane. The LS-DYNA card *CONTACT AUTOMATIC SINGLE SURFACE defines all interfaces within the model except the welds. LS-DYNA automatically simulates both impact and sliding along interfaces. For this analysis, the non-default soft constraint method used calculates the stiffness of the linear contact springs based on the contacting nodal masses and the global time step size.

For the top and side drop cases, an initial velocity (*INITIAL_VELOCITY) is applied to the model to simulate the 360-in (9-m) free drop. Knowing that the potential and kinetic energies are equal on impact, the initial velocity is

$$\frac{1}{2}\mathrm{MV}^2 = \mathrm{MGh} \Rightarrow \mathrm{V} = \sqrt{2\mathrm{gh}} = \sqrt{2\left(386.4\,{}^{\mathrm{in}}/_{\mathrm{sec}^2}\right)(360\ \mathrm{in})} = 527.5\,{}^{\mathrm{in}}/_{\mathrm{sec}} \qquad (1)$$

For the 35° slap-down / whiplash analysis, the kinetic energy is a function of the distance the center of gravity of the package travels to contact the impact plane [Ref. 1, Supplement 1]. The kinetic energy is calculated by adding the drop height 360 in (9 m) to the distance from the center of gravity to the impact plane. Therefore, the effective drop height of the slap-down / whiplash is 426.54 in (10.83 m) as compared to the top drops of 372.36 in (9.46 m).

The drop energy is calculated by multiplying the drop height times the weight. For the LS-DYNA model the total weight is 2,653 lb (11,801 N). Therefore, the total energy absorbed during impact is 1.132E+06 lbf-in (1.276E+05 N-m) for the whiplash case as compared to 9.878E+05 lbf-in (1.116E+05 N-m) for the top drop. To simulate the whiplash in LS-DYNA, an angular velocity, omega, is applied at the point of impact using the LS-DYNA command *INITIAL VELOCITY GENERATION. The angular velocity is -5.05 rad/s.

Post-Processing of Results

Nodal output is stored by LS-DYNA using the *DATABASE_HISTORY_NODE command. Output of individual nodes collecting acceleration data is piped to as an ASCII text file database called NODOUT. Subsequent post-processing of the nodal results is accomplished by starting the program LS-PREPOST from the LS-DYNA manager. For this evaluation, acceleration data is collected for a series of nodes. One node is placed on the fuel bundle to determine the maximum contents acceleration.

Side Drop: The LS-DYNA analysis shows that variations in payload weight cause increased accelerations of up to +5% when the lightest fuel bundles are evaluated and decreased accelerations of approximately 9% for the heaviest bundle configuration. The LS-DYNA analysis shows that the temperature variations in the shock absorbing materials affect transmissibility. The maximum acceleration occurs, when the temperature is -40°C.

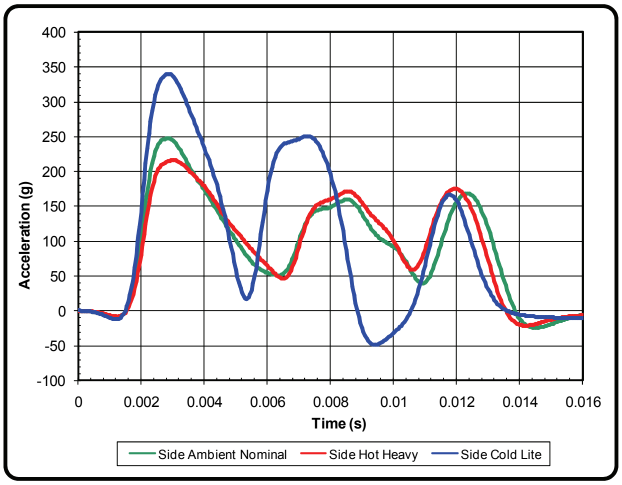


Figure 7 – Side Drop Accelerations (Cold, Ambient, and Hot)

The RAJ-II side drop acceleration time histories at cold, ambient, and hot conditions are presented in Figure 7. Because of the crush characteristics of the honeycomb, the maximum predicted acceleration occurs with the lightest fuel weight at the coldest temperature (-40°C). The peak acceleration reported during the side drop is 340g at 500 Hz.

Top Drop: Figure 8 provides a comparison of the RAJ-II top drop at cold, ambient, and hot conditions. Like the side drop, the combination of extreme cold temperatures (-40°C) and lightest bundle weight results in the maximum acceleration. The peak acceleration reported during the top drop is 186g at 500 Hz.

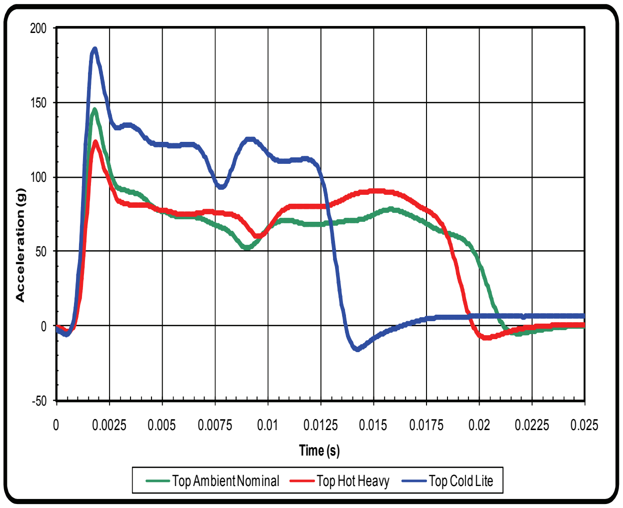


Figure 8 - Top Drop Accelerations (Cold, Ambient, and Hot)

Slap-down/Whiplash: Figure 9 compares the whiplash and top drop results. The analysis results show that the RAJ-II is more efficient during the slap-down event than the flat top drop. During slap-down, honeycomb surface area is initially only available at the point impact and gradually increases as the impact progresses. During the flat top or side drops, the projected area of the honeycomb contacts the inner container at impact initiation resulting in maximum stiffness of the honeycomb. Therefore, the initial peak acceleration is much higher during the flat top or side drops than when the container impacts at an angle where the contact area is much smaller.

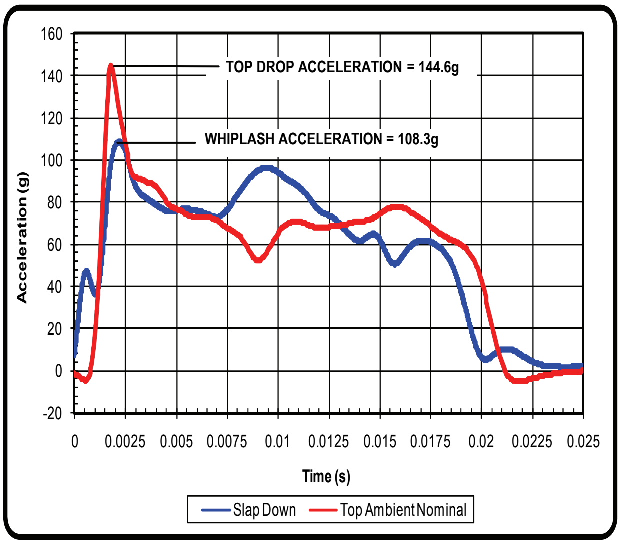


Figure 9 - Top Drop versus Slap-down Accelerations

Comparison of FEA Results and Historic Tests

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 Ethafoam 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 RAJ is essentially the same design as the RA-3 with a carbon steel inner container, no thermal insulation, and a wooden outer container. The RA-3D design is an exact copy of 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. Because of concerns about decontamination and maintenance, the wooden outer container was replaced with stainless steel. An additional improvement to the outer container included the addition of a vibration isolation frame that reduces the amount of high cycle vibrations to the fuel bundles during normal transportation.

To benchmark the LS-DYNA analysis results, historic drop tests are used. Because instrumented side drop testing was not performed on the RAJ-II, the LS-DYNA analysis results are compared to the RA-3D testing program. The RA-3D provides an ideal comparison to the RAJ-II because dimensionally, the RA-3D is almost identical to the RAJ-II in length, width, and height.

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. 4]. Figure 10 provides a comparison of the RA-3D drop test and RAJ-II LS-DYNA analysis results. The comparison shows good agreement where 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. To further benchmark these results, a hand calculation predicts the peak acceleration. This is possible because of the simple geometry of the RAJ-II and RA-3D honeycomb design. Reasonable estimates of the drop accelerations are possible by using the methodology presented in Reference 5. Table 1 is a summary of the calculations used to estimate the accelerations of the RA-3D and RAJ-II. Figure 10 compares the acceleration predictions with the drop test and analysis results.

$$G_m = \mathrm{DLF} \times \sqrt{\frac{2hk_2}{W_w}}, \text{ acceleration of contents} \tag{2}$$

Where,

h = Drop height (in)
W_2 = Weight of the packaged article (lb)
$k_2 = \frac{P_m}{x_c}$, Linear elastic spring rate (lb/in)
$Pm = \frac{\sigma}{A}$, Force on contents by cushioning (lb)
σ = Crush strength of the material (psi)
A = Projected area of the honeycomb (in^2)
x_c = Height of the honeycomb (in)
DLF = Dynamic load factor [Ref. 6, p2.8-3]

Table 1 – Acceleration Prediction Using Hand Calculations

Variable	RAJ-II	RA-3D
G_m	228.5	391.2
h	360.00	360.00
W_2	2187.00	2094.39
k_2	176831.50	573231.67
P_m	245107.09	333044.93
σ	290.00	205.00
A	845.20	1624.61
x_c	6.18	2.99
DLF	2.00	2.00

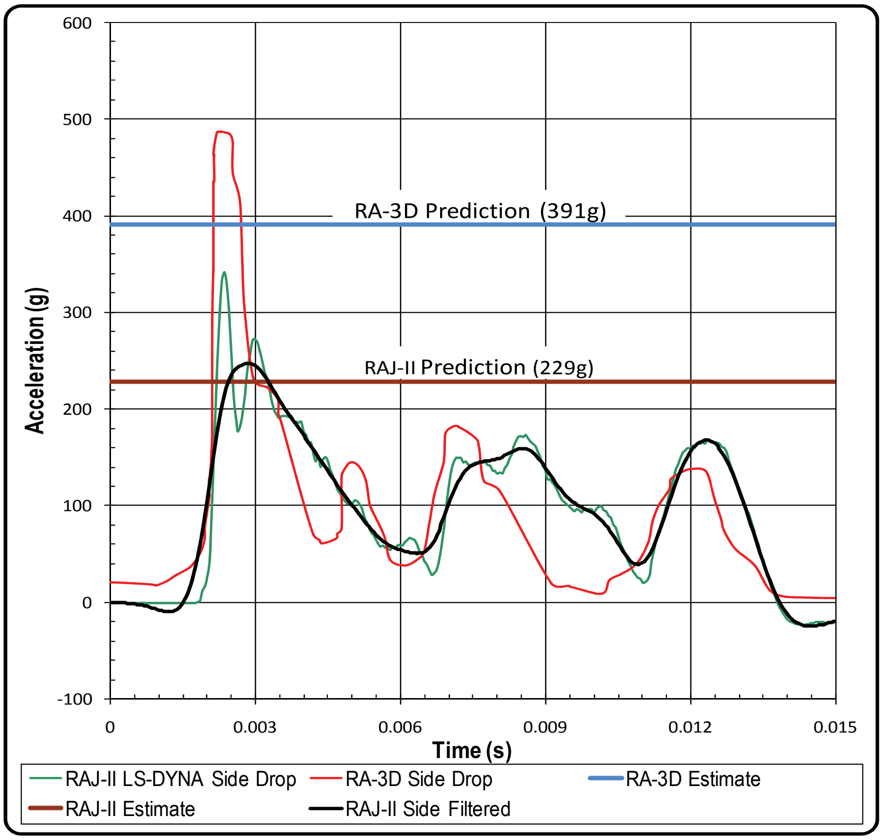


Figure 10 – LS-DYNA, RA-3D Test, and Hand Calculations

The hand calculation confirms that the RA-3D test and RAJ-II LS-DYNA results reasonably predict the acceleration response of the contents.

Independent Verification

Because the LS-DYNA model is sufficiently complex, the method of verification consists of a set of idealized hand calculations to verify the slap-down event. These hand calculations utilize the same linear elastic model as presented in Reference 5. To facilitate the hand calculations, the single problem is split into two smaller components for simplicity.

The first component consists of the initial impact on the top corner edge of the RAJ-II lid. The acceleration is calculated based on the conservative assumption that the total kinetic energy is dissipated by the crushable material without changing the orientation of the container. Additionally, the load is considered to be carried by only the cross section of the honeycomb block supported by the bottom of the container parallel to the acceleration

The second component calculates the acceleration based on a flat impact similar to the top drop. The height utilized for the "second drop" during the slap-down event is based on the distance of the center of gravity from the impact plane at the instant of contact. The deflection required to absorb the energy from the first component is used as the initial condition to calculate this secondary acceleration. Since the impact is essentially flat, the entire cross section of the block is available to absorb the remaining kinetic energy.

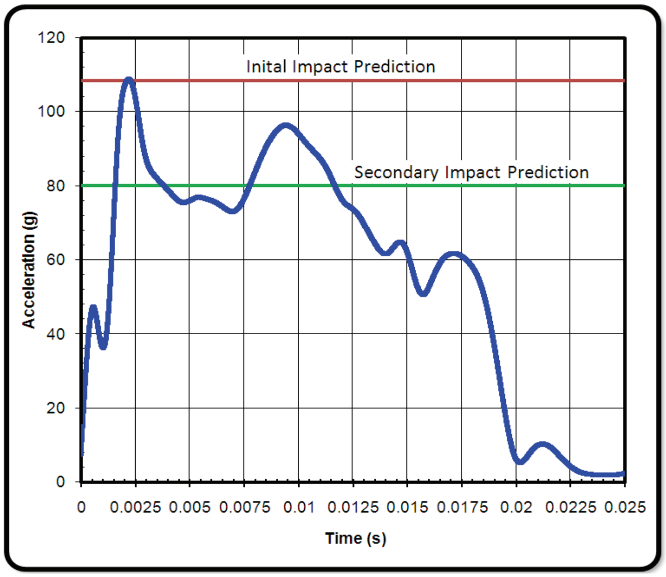


Figure 11 – LS-DYNA Slap-down Results versus Predictions

The acceleration calculated for the first component is approximately 110g, and the peak acceleration calculated for the secondary slap-down is approximately 80g. Figure 11 compares these predictions to the accelerations calculated by LS-DYNA.

As Figure 11 shows, the peak acceleration calculated for the initial impact is within 2g of the acceleration predicted by LS-DYNA (110g versus 108.3g). The hand calculation estimates a lower acceleration for the secondary peak as compared to LS-DYNA (80g versus 96.3g). However, this verification method adequately estimates the peak acceleration and closely corresponds to the values predicted by the computer model.

CONCLUSIONS

This evaluation shows that testing, finite element analysis, and first principle calculations are all valid methods for evaluating the performance of a package, when the geometry and materials are well defined. When all three methods are utilized, it is possible to benchmark analytical models that can be used to further improve packaging design.

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