PROTECTING AGAINST CORNER IMPACTS: SENSITIVITIES DISCOVERED DURING A RAIL CASK IMPACT LIMITER DESIGN

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ABSTRACT

Type B packages for the transportation of radioactive materials must remain "essentially leak tight" under severe regulatory accident conditions, defined in the U.S. Nuclear Regulatory Commission's 10 CFR 71.73 and the International Atomic Energy Agency's TS-R-1. The 9-m free drop test requirement onto an unyielding surface is performed in an orientation "for which maximum damage is expected". Analytical techniques are used to evaluate various possible impact orientations before testing, and historically these maximal damage orientations have been side, slap-down, end, and center-of-gravity over corner (CGOC). Other orientations are rarely considered.

Sandia National Laboratories (SNL) was asked by Equipos Nucleares, S.A. (ENSA) to design, analyze, and test an impact limiter system for a newly designed rail cask. During the conceptual design process, SNL performed due diligence and evaluated a wide spectrum of possible impact orientations, in order to assure that peak cask body acceleration design goals were not exceeded. But design of the impact limiter, including not only crush strength of constituent materials (which can be orientation and temperature dependent), but also the shape of the impact limiter, greatly affects peak acceleration response during 9-m drops in various orientations.

Although many impact limiter design shapes resemble truncated right circular cylinders attached to each end of the cask, some tend to round the outer corners or truncate those corners with conical sections. SNL's original conceptual design followed a similar theme, intending to use polyurethane foam or aluminum honeycomb within a beveled-corner shaped cylindrical shell. Detailed finite element analyses indicated excellent impact resistance at regulatory cold temperatures in the stereotypically-tested side, slap-down, end, and CGOC impact orientations. Shortly before proceeding to engineering design, a rarely-considered impact orientation of 45 degrees from horizontal indicated that cask body acceleration levels jumped unexpectedly, exceeding the design goal due to insufficient crushable material protecting the sharp corner of the cask. A complete re-design of the impact limiter was necessary, and the lessons learned from this experience could have implications for future impact limiter designs, and possibly existing designs that may not have considered this atypical impact orientation during the design process.

INTRODUCTION

Impact limiters for Type B packages are typically designed to limit peak cask body accelerations below an acceptable level, without significantly impeding the path of decay heat from spent fuel. The containment boundary is often designed using the peak "rigid body" acceleration field essentially as a load to calculate resultant stresses, ensuring that design stress limits are not exceeded, and that the containment boundary remains essentially leak tight. SNL designed an impact limiter system for ENSA's ENUN 32P rail cask based on a 60-G acceleration limit and an outer diameter handling constraint.

Aluminum honeycomb was initially chosen as the impact limiting material (within a thin ductile stainless steel skin) because its crush strength behavior is insensitive to hot or cold temperature variation. The shape was chosen to minimize weight and cost of the impact limiting honeycomb, and was noted to be similar to other existing impact limiter designs [1, 2, 3]. Impact limiter material crush strength and outer dimensions were initially selected using hand calculations and energy balance methods. Finite element analyses were necessary to accurately quantify the dynamic impact limiter behavior and cask acceleration response during 10 CFR 71.73 [4] and IAEA TS-R-1 [5] regulatory accident conditions.

CONCEPTUAL DESIGN ANALYSES

The initial conceptual impact limiter design, shown in Figure 1 after a 9-m side drop impact, assumed the use of various sections of directional aluminum honeycomb of sufficient crush strength to protect against the typical regulatory tested end, side, CG-over-corner, and slap-down impact orientations. The approximately 38-G peak (100 Hz filtered) vertical acceleration is well below the 60-G limit.

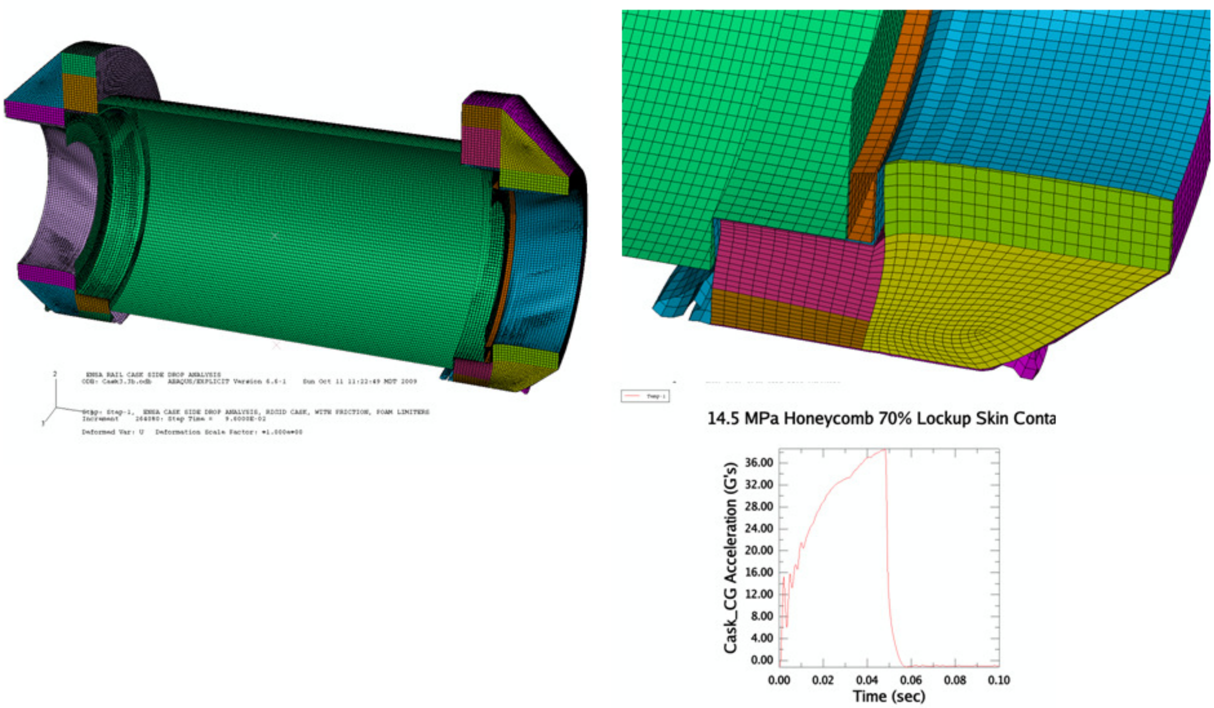

Figure 1: Impact Limiter Conceptual Design After Side Impact

Figures 2, 3, and 4 show the conceptual impact limiter deformations and rigid cask vertical accelerations for end, CG-over-corner, and slap-down 9-m drop impacts. Note that all peak acceleration levels are well below the design goal 60-G limit.

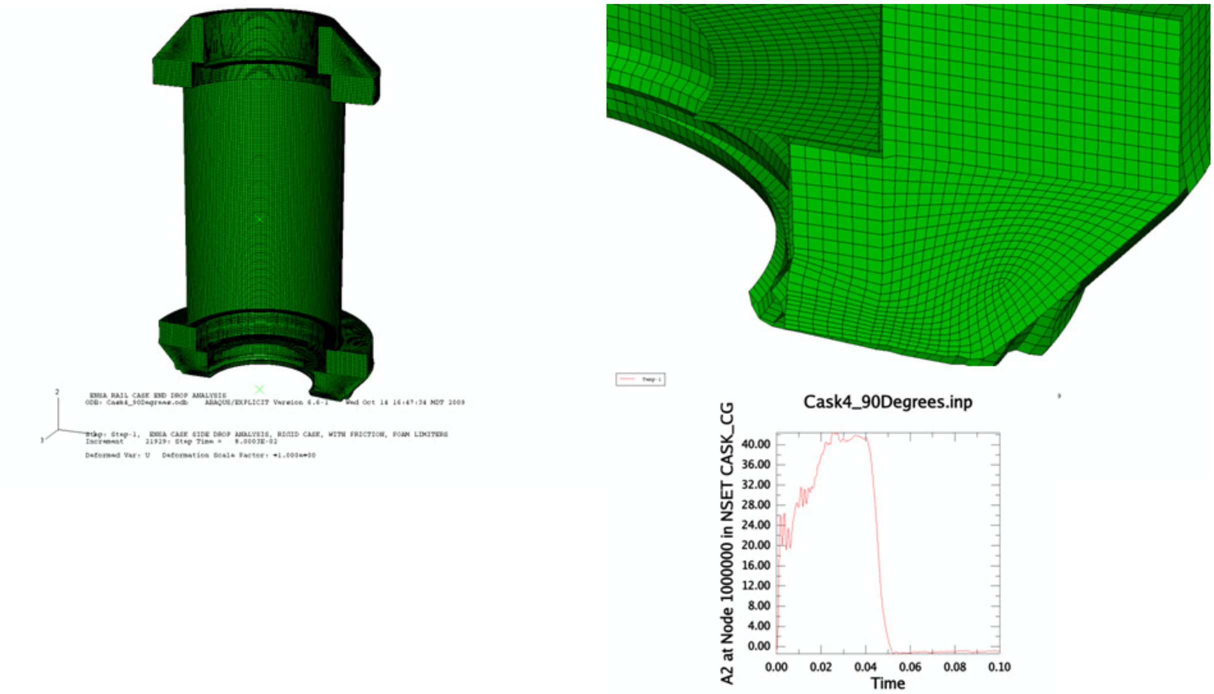

Figure 2: Conceptual Impact Limiter After End Impact

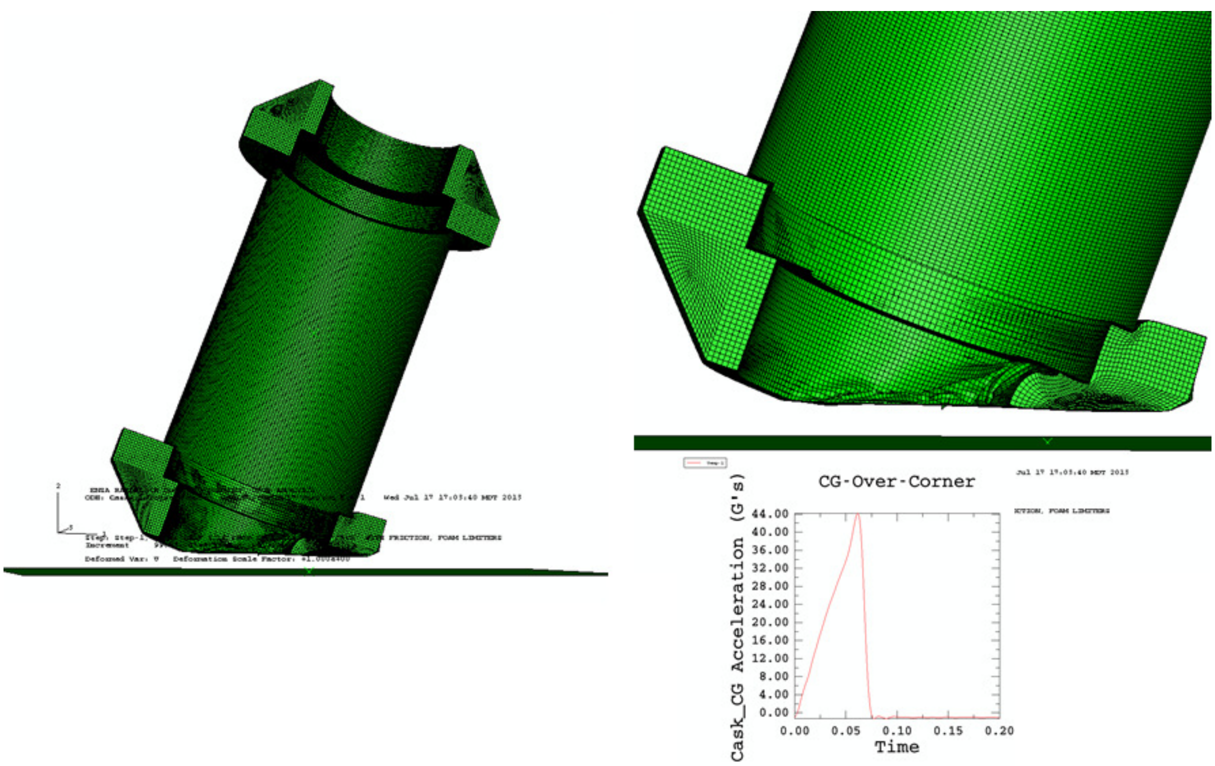

Figure 3: Conceptual Impact Limiter After CG-Over-Corner Impact

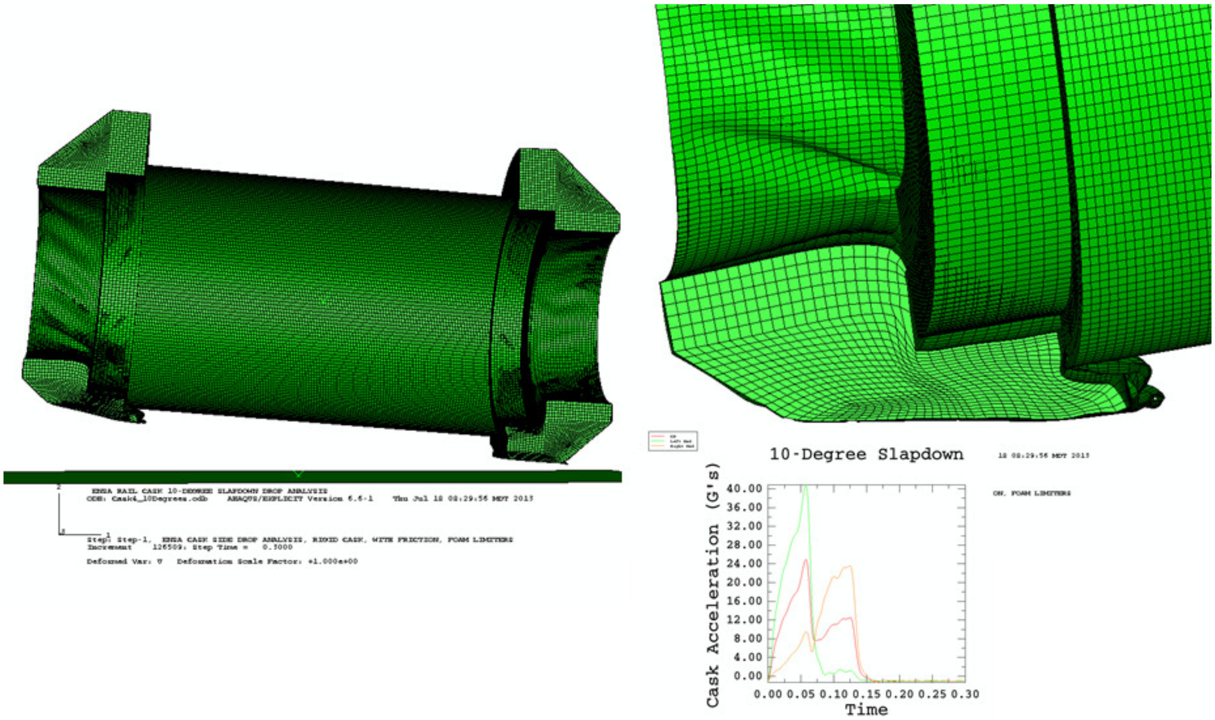

Figure 4: Conceptual Impact Limiter After Slap-Down Impact

Although the conceptual impact limiter design appears to meet all design requirements in the stereotypically-tested impact orientations, its beveled-corner shape hints that another impact orientation is worth additional consideration. An essentially 45-degree impact (after a 9-m drop onto an unyielding target) would create an impact limiter to target contact with the beveled surface parallel with the target surface. This orientation is almost never considered in regulatory tests (and often not in certification analyses) because it imparts less energy into the corner of the impact limiter that CG-over-corner impacts, and less energy into the side of the impact limiter than side or slap-down impacts; it appears to be more benign.

Analysis of this case (as shown in Figure 5), however, shows that because the conceptual impact limiter shape has less material in a direction normal to the beveled surface, “lockup” of the material occurs and the cask CG vertical acceleration spiked to greater than 100 Gs, well beyond the design goal limit. Even using honeycomb with more than double the crush strength resulted in about 100 Gs of CG vertical acceleration, exceeding the design limit. After about 70% nominal strain, the aluminum honeycomb has completed its crushable range and the force or stress transmitted, goes up rapidly. This conceptual design impact limiter shape “should” not pass regulatory review because it could yield excessive containment boundary deformations due to high accelerations in this impact orientation. Thus, the impact limiter must be re-designed to protect the cask better in this atypical 45-degree impact orientation, as well as the typical side, end, CG-over-corner, and slap-down orientations.

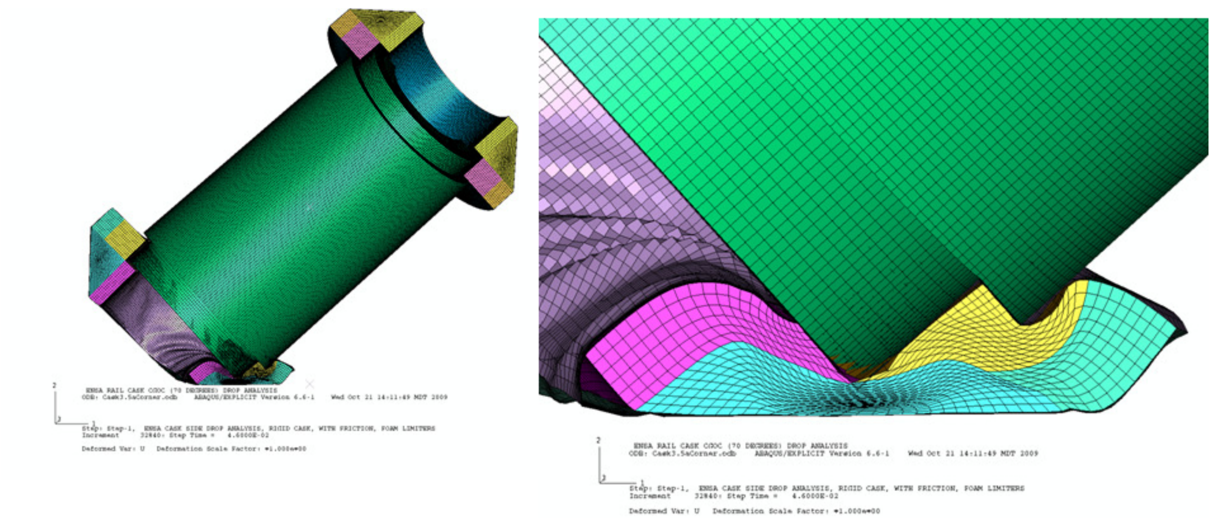

Figure 5: Conceptual Impact Limiter After 45-Degree Impact (Peak Acceleration ~100 G's)

IMPACT LIMITER REDESIGN

Although higher density (stronger crush strength) honeycombs were tried in the beveled region of the previous conceptual impact limiter design to avoid lockup, acceleration limits continue to be exceeded. There was merely insufficient crushable material in this region. Because honeycomb is more expensive than rigid polyurethane foam, and is somewhat difficult to properly orient its strong crush axis for all possible impact orientations, a larger volume of rigid polyurethane foam was chosen to provide end and corner impact protection. Outer diameter size constraints on the impact limiter for handling and transportation dictated the continued use of honeycomb crushable material protecting the side and slap-down orientations. However, the lack of length constraints led to the design change of using a significantly larger volume of rigid foam in the end portion of the impact limiter, creating a composite design of both honeycomb and foam.

The acceleration of the cask is proportional to the crush strength of the material being crushed and the area of material being crushed. The "footprint" or crushable area in each possible impact orientation must be balanced with the crush strength of the material crushed in each orientation to ensure that acceleration levels meet design goals or limits, including avoidance of insufficient material or crush strength, which could lead to excessive impact limiter deformation and lockup, which then spikes cask accelerations. Additionally, foam rise direction, manufacturing variability, and the temperature sensitivity of foam must be considered because crush strengths can vary in rigid polyurethane foam by almost 500% when all three of these factors are combined in regulatory hot vs. cold conditions (in part because of the decay heat from the fuel).

In order to adequately protect the cask in 45-degree impacts without exceeding side and end impact acceleration limits due to combined crush strength vs. large footprint considerations, a lower crush strength foam was chosen as a replacement material. Additionally, the shape of the impact limiter end was designed to be conical, to minimize end impact footprint and reduce peak accelerations in side and end impact orientations without resorting to more complicated multiple pours of multiple foam densities. Initial analyses showed excellent impact protection. The final impact limiter design is shown in Figure 6, with each impact limiter being attached with long end bolts to minimize worker exposure to radiation and provide sufficient bolt elasticity to withstand the large tensile and bending loads during 9-m drop impacts. Gussets were used to reinforce the bolted connection.

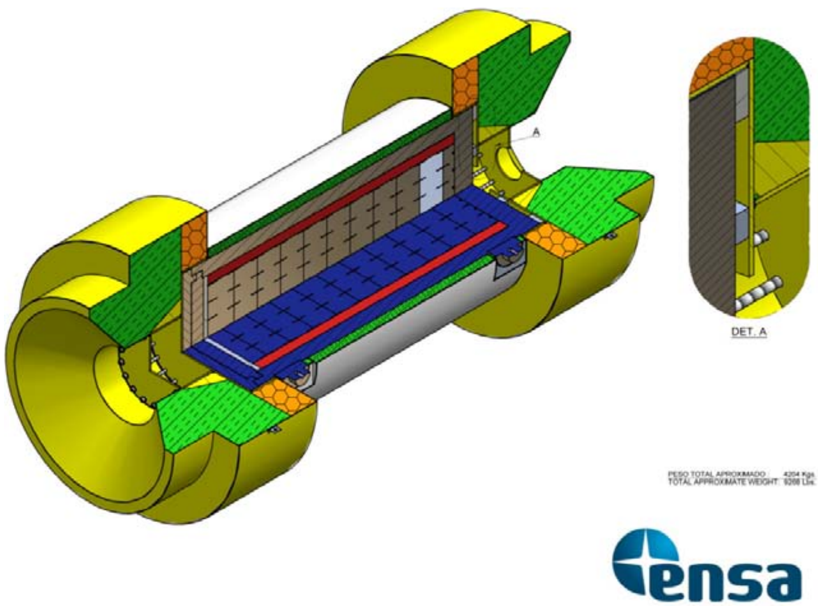

Figure 6: Updated Impact Limiter Design for ENSA ENUN 32 Cask

1/3-SCALE VALIDATION TESTING ANALYSES

Although initial impact analyses with the updated impact limiter design indicated that peak acceleration limit design goals would be met, 1/3-scale impact tests were performed to provide additional confidence in the impact limiters' design performance. 10 CFR 71.71 normal condition 1-m side drop, side and end puncture drops, and hot and cold 9-m drops in side, end, CG-over-corner, and slap-down orientations were performed at SNL. These tests were performed to both increase regulators' confidence in the overall package performance and provide validation data for 1/3-scale analyses under the same conditions as tested.

Peak accelerations from all of the drop tests were below the full-scale equivalent design goal of 60 Gs. Scaling laws indicate that full-scale accelerations are 1/3 the magnitude of those tested in 1/3-scale. An example comparison of the 1/3-scale test results (from both filtered accelerometers data and optical tracking data in Figure 7) and the 1/3-scale side impact analysis in Figures 8 and 9, is shown below. The poured-in-place rigid polyurethane foam bonds well with the thin stainless steel walls of the impact limiter skin, although some de-bonding may occur during large deformations an in localized buckling. In the scale-model analyses, frictional sliding foam-to-stainless steel contact, as well as fully tied or bonded contact was modeled, and the tied contact better bounded the acceleration levels and fairly well approximated the duration of the impact event. From the figures, good correlation between the peak acceleration magnitude and duration is seen, and this provides confidence that the same explicit dynamic finite element analysis methodology applied to a scaled-up full-scale model would accurately predict impact limiter and package performance in regulatory accident conditions.

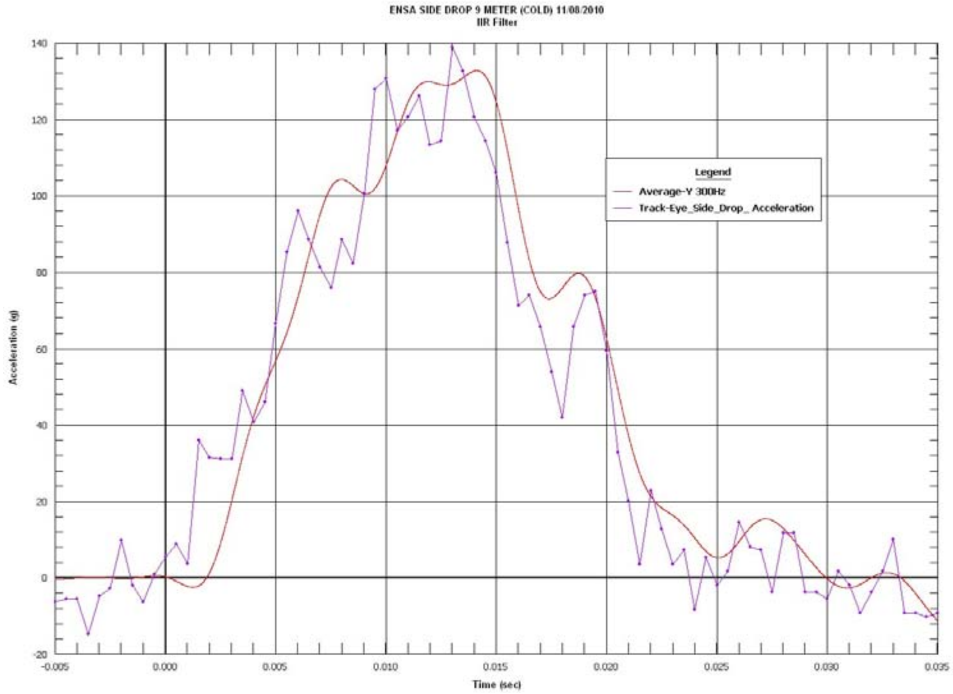

Figure 7: 1/3-Scale 9-m Cold Side Drop Test Cask CG Vertical Accelerations

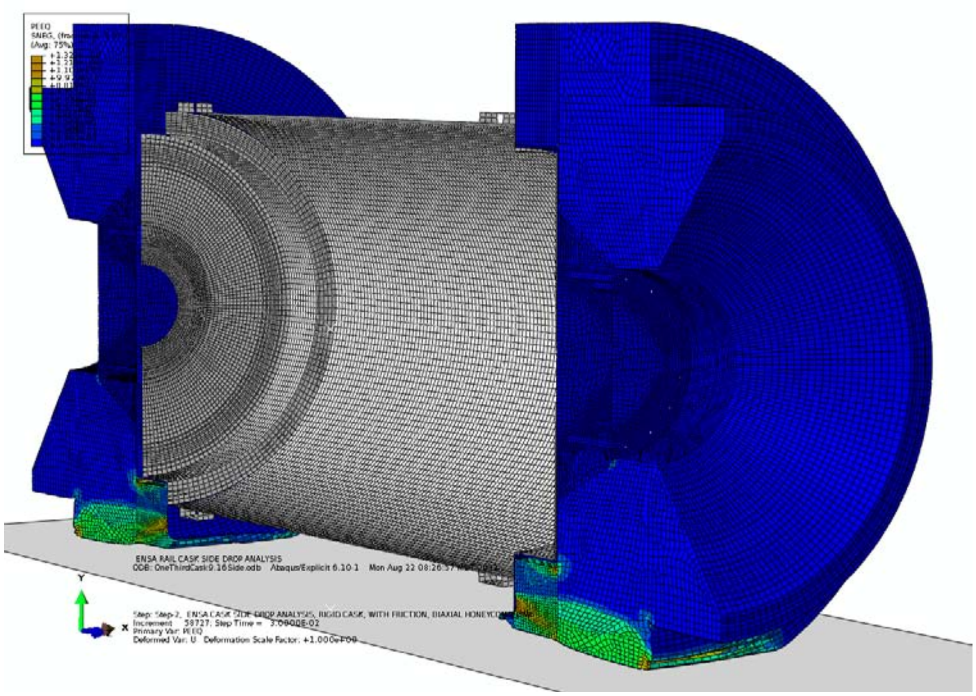

Figure 8: 1/3-Scale 9-m Cold Side Drop Analysis Impact Limiter Deformation

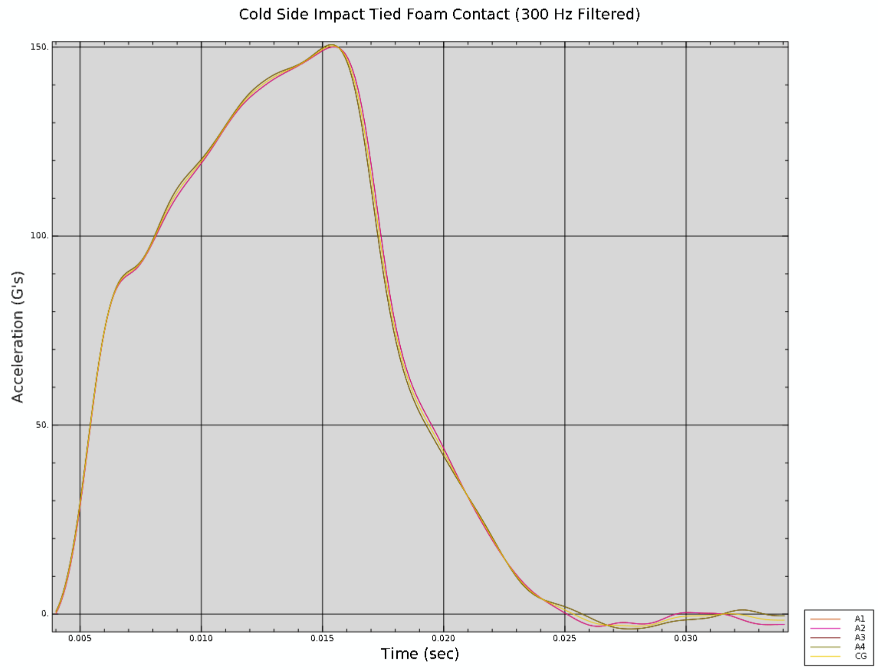

Figure 9: 1/3-Scale 9-m Cold Side Drop Analysis Cask Vertical Accelerations

BOUNDING CERTIFICATION ANALYSES

Detailed explicit dynamic finite element analyses of the full-scale ENSA cask under 9-m regulatory accident impacts in numerous impact orientations were performed by SNL to support certification of the transport cask and impact limiters. Bounding analyses were performed to yield "worst case" acceleration levels, ensuring they would always remain below the 60-G design goal. At regulatory cold conditions, for example, cask decay heat was ignored and the entire impact limiter was assumed to be at -29 degrees C (-20 degrees F). Additional margin was implied by also assuming that the foam and honeycomb crush material crush strengths were 15% stiffer than nominal, to account for variation due to manufacturing tolerances. In regulatory hot conditions (38 degrees C, or 100 degrees F), the cask's decay heat was accounted for via detailed ENSA thermal analyses, which showed that the peak impact limiter material temperatures could be as high as 128 degrees C (260 degrees F) (and as low as 44 degrees C or 111 degrees F). Conservatively, all the foam impact limiting material was assumed to be at the highest possible temperature, and additional margin implied by using foam and honeycomb crush strengths 15% below nominal for the respective temperatures. Foam properties were also rise-direction (along cask axis) dependent, and off axis impacts always assumed the more conservative rise direction to either maximize acceleration (in cold conditions) or displacement in hot conditions, in order to verify that lockup would not occur and subsequently spike acceleration values.

The regulatory cold side impact analysis results for a 9-m drop of the full-scale cask onto an unyielding target are shown below in Figures 10 and 11.

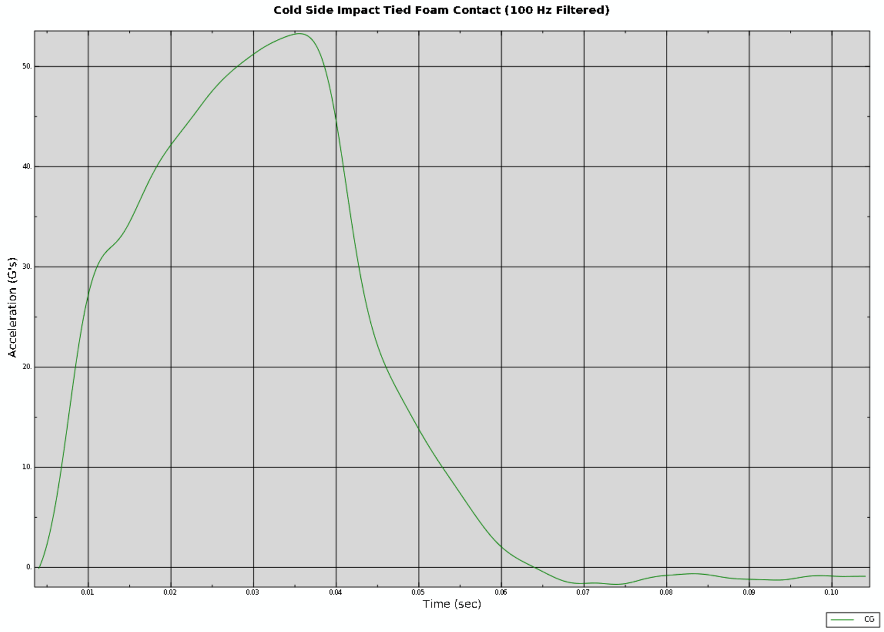

Figure 10: Full-Scale 9-m Cold Side Drop Analysis Cask Vertical Accelerations

The peak acceleration (100 Hz Butterworth filtered) is below the 60-G design goal, and impact limiter deformation and buckling patterns are similar to those previously tested. Although results for the other typical impact orientations and temperatures are not shown for brevity, acceleration levels always remained below the design goal level. Even in the regulatory hot bounding calculation, assuming all foam at the highest temperature and foam/honeycomb crush strengths 15% below nominal, no foam lockup occurred, nor did cask lifting trunnion contact with the rigid target occur (which would exceed acceleration goals).

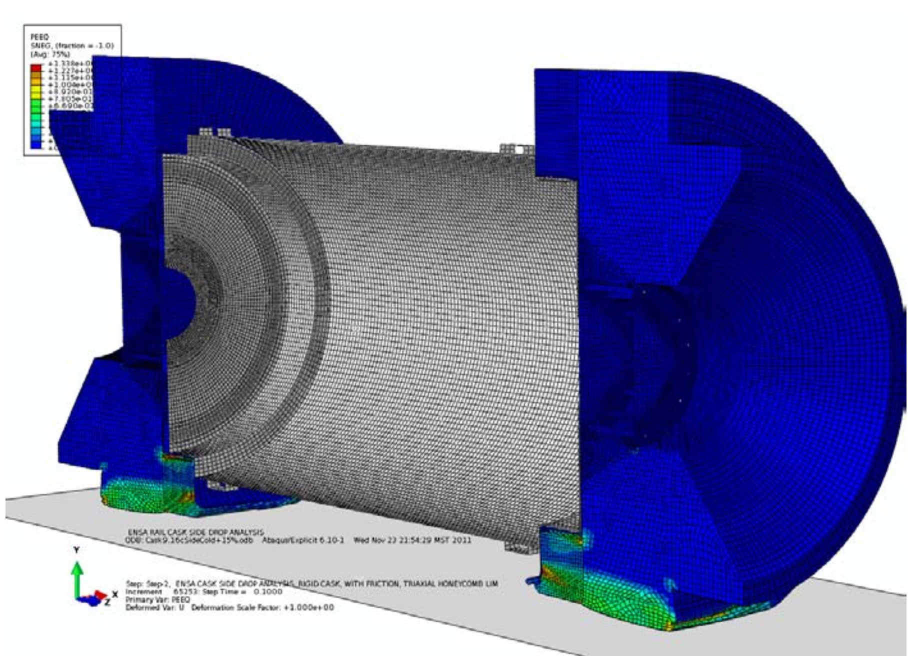

Figure 11: Full-Scale 9-m Cold Side Drop Analysis Impact Limiter Deformation

The primary reason for the impact limiter re-design effort was the conceptual design's unacceptable performance in the atypically-evaluated 45-degree impact orientation. The new design has significantly more impact limiting material (foam), protecting the corners for all possible impact orientations. An analysis of the 45-degree orientation case, under conditions producing the largest possible impact limiter deformation, was performed. Honeycomb and foam strengths were 15% below nominal, for manufacturing tolerance bounding, and all foam was at the hottest possible parallel-to-rise (weakest) crush strength. The peak acceleration was well below the 60-G design goal, but more importantly, sufficient impact limiting material exist to avoid foam lockup, which would have caused the acceleration to rise sharply. The filtered acceleration history and impact limiter deformation are shown in Figures 12 and 13. Thus, this impact limiter design was shown via scale-model analyses, validation testing, and bounding certification analyses to protect the ENSA 32P rail cask in all possible regulatory accident conditions.

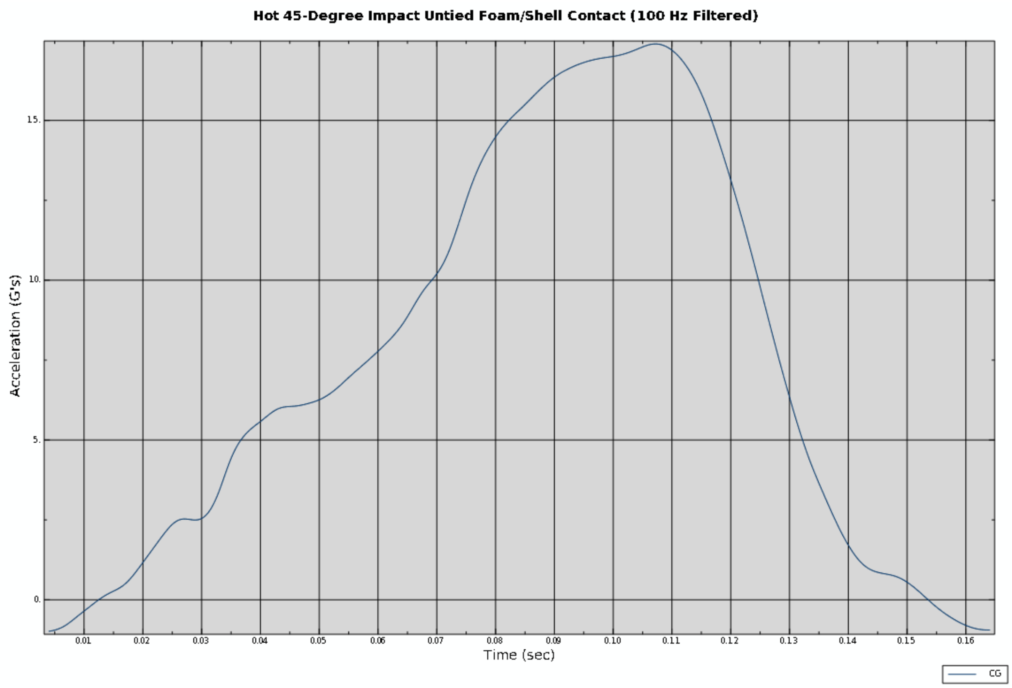

Figure 12: Full-Scale 9-m Hot 45-Degree Drop Analysis Cask Vertical Accelerations

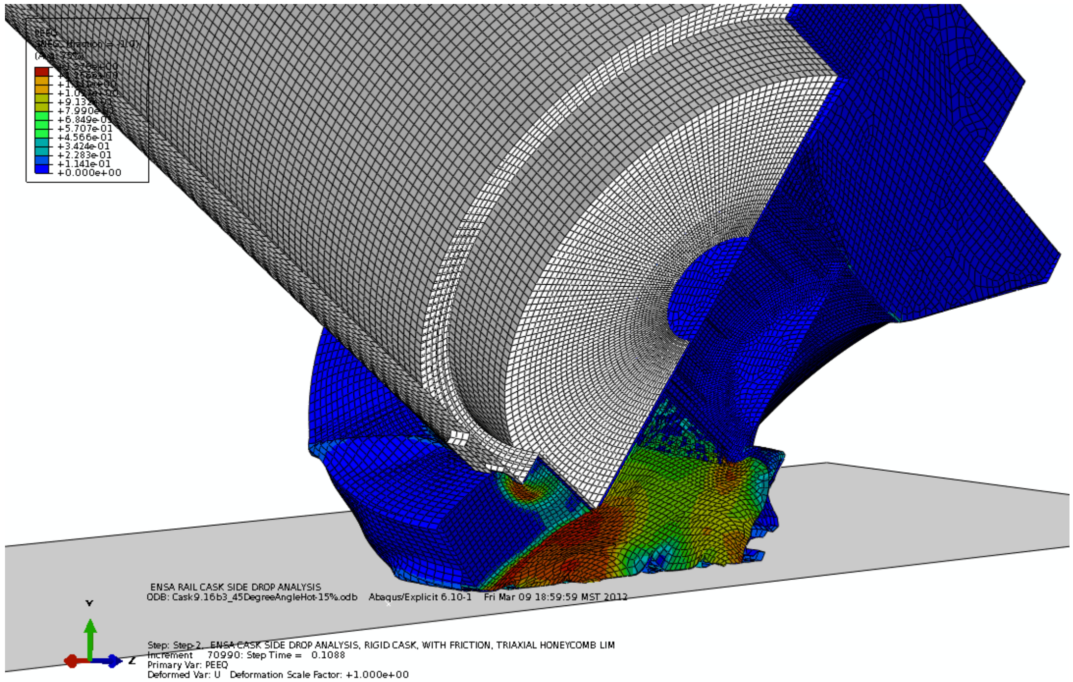

Figure 13: Full-Scale 9-m Hot 45-Degree Drop Analysis Impact Limiter Deformation

SUMMARY AND CONCLUSIONS

SNL successfully designed, tested, and performed certification analyses on a new rail cask for ENSA. An initial conceptual design that performed well in the typically-tested side, end, CG-over-corner, and slap-down 9-m drop impact orientations, performed poorly in an often-ignored 45-degree impact orientation. A complete re-design of the impact limiter was necessary, but the new design was shown (through scale-model analyses, validation testing, and bounding full-scale certification analyses) to adequately protect the package in all impact orientations. This lesson learned should highlight the need for packaging designers to evaluate all possible impact orientations, including a range of slap-down orientations as well as atypical orientations, such as 45-degree impacts.

ACKNOWLEDGMENTS

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