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Modeling and Analysis of a One-Third Scale Used Nuclear Fuel Package 30 cm Drop

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ABSTRACT

This paper compares finite element models of used nuclear fuel package drop tests to actual test data recorded in a recent test campaign. In December of 2018, the US Department of Energy collaborated with Equipos Nucleares S.A, S.M.E (ENSA) and Bundesanstalt für Materialforschung und -prüfung (BAM) to perform 30 cm horizontal drop tests of a one-third scale model of the ENSA ENUN 32P dual-purpose used nuclear fuel package. The third-scale test package included a third-scale basket and simulated third-scale fuel assemblies that were instrumented with accelerometers to measure their individual impact responses. Two horizontal package drop tests were performed, one with the basket cells oriented parallel and perpendicular to the impact surface, and one with the basket rotated 45 degrees to change the relative orientation with the impact surface. This paper describes the modeling and analysis that supported the development of the test and instrumentation plan, such as which fuel assemblies should be instrumented and at what locations on each fuel assembly should the accelerometers be placed. Pre-test predictions based on finite element modelling are discussed, and a comparison against the actual test data is made. Post-test analysis and model refinement are also discussed, with the goal of identifying best practices and lessons learned. A separate paper by Kalinina et al., to be presented at this conference, more fully describes the test configuration and test results. This paper is focused on the numerical modeling that supported the test and the lessons learned about realistically modeling this type of physical test.

INTRODUCTION

In December of 2018, the US Department of Energy collaborated with Equipos Nucleares S.A, S.M.E (ENSA) and Bundesanstalt für Materialforschung und -prüfung (BAM) to perform 30 cm horizontal drop tests of a one-third scale model of the ENSA ENUN 32P dual-purpose used nuclear fuel package. Similar reduced scale testing of packages is commonly done to support safety basis analyses of packages, but this test was different because it included fuel assembly surrogates that were instrumented with accelerometers to record the impact response of fuel assemblies and the fuel basket, inside the package. Accelerometers also measured the acceleration outside of the package and the acceleration of the impact target surface. All of the various data channels provide a valuable set of data that can be used to study the impact dynamics of the system and validate explicit dynamic finite element models of the test configuration.

The motivation for this experimental work was to characterize fuel assembly impact loads to fill a knowledge gap in the structural analysis of fuel assemblies and prepare for a future full scale fuel assembly drop test campaign. A more complete description and discussion of the test program and test results is covered in [1]. This paper focusses on the engineering mechanics and finite element analysis (FEA) aspects of the package drop test. FEA was used to make pre-test predictions of the package system impact response to a 30 cm horizontal drop. Those results were used to recommend instrumentation locations. The pretest prediction model also provided a virtual test environment, where different impact orientations could be considered. This led to a recommendation to perform a second drop test with a 45-degree axial rotation of the package. This paper describes the FEA results and compares them to the recorded test data.

ONE-THIRD SCALE PACKAGE MODEL

The package is modeled in LS-DYNA [2] a commercial general-purpose explicit dynamic finite element code that is well-suited to structural dynamic impact modeling. The model is a three dimensional representation of the ENUN 32-P dual purpose cask system. Figure 1 shows the package model in its half-symmetry configuration. A full 3-D model was also generated from the half-symmetry finite element mesh (a mirror element generation) and used for final impact response calculations. This paper will clarify when the symmetry or full 3-D versions of the model were used.

The geometry of the FEA model generally matches the scale test package in terms of mass and major dimensions. One simplification in the FEA model is that the cask body is approximated as a closed cylinder, rather than modeling the bolted lid in detail. For safety analysis models, the bolted lids are key features for evaluation, but in this application the lid area response is not relevant. Bolts provide sufficient tensions and clamping force that the lid response is not expected affect the rest of the package. Similarly, the impact limiters are modeled with homogenous volumes of material (regions of polyurethane foam and aluminum honeycomb) instead of representing the details of the sheet metal impact limiter skin, impact limiter bolted attachment, or other precise details of the impact limiter. This is a simplified way to model impact limiters, but previous impact test data was available to choose crushable material properties to reasonably match the impact behavior. The package model impacts a perfectly rigid surface, so the crush strength of the foam and honeycomb materials are the primary parameters used to achieve the desired impact behavior.

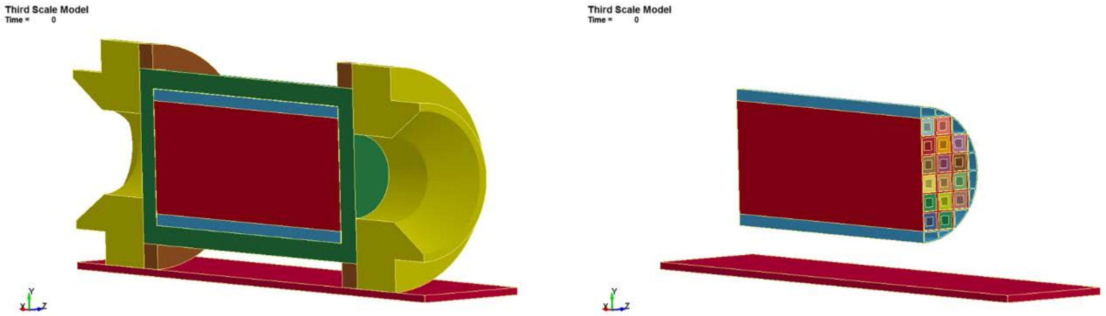

Figure 1: Package Model (Half Symmetry)

The simulated (sometimes called "dummy") fuel assemblies used in the test are square steel tubes that have slots cut out of them. The FEA geometry is shown in Figure 2. The labels A, B, C, and D identify the relatively solid sections where the square tube is not modified by slots. Location A is closest to the package lid, and location D is at the opposite end, closest to the package base plate. The next section discusses how the accelerometer locations were chosen.

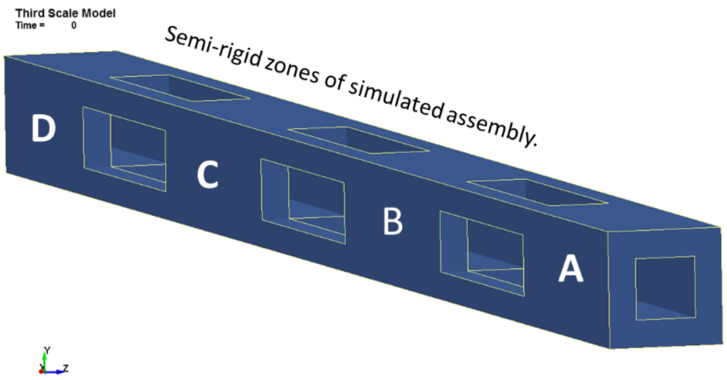

Figure 2: Surrogate (Dummy) Fuel Assembly

Most of the FEA model used the linear elastic material model: simulated assemblies, package body, basket, and basket rails. The impact surface was a rigid structure. The impact limiters used LS-DYNA's *MAT_MODIFIED_HONEYCOMB model.

The package model was loaded with an initial velocity of 2.44 m/s, to represent a 30 cm drop. Note that all analysis cases discussed in this paper represent 30 cm horizontal package drops. A single, all-inclusive contact definition was used to detect contact between all of the individual components in the model.

INSTRUMENTATION RECOMMENDATIONS

One of the roles of FEA in this task was to make recommendations for where to place accelerometers or other transducers in the test plan. The half-symmetry model was run to calculate an initial estimate of the system response to a 30 cm impact. The results were studied to determine the ideal locations for accelerometers to be placed on the simulated fuel assemblies to measure the impact response. The conclusion was that the response of the simulated assembly is expected to be dominated by rigid body motion, not flexure. It was recommended to place accelerometers at A, B, C, or D, away from the edges or slots.

The FEA results were also used to select the fuel assemblies for instrumentation in the test plan. The FEA-calculated acceleration pulse for the center of mass of each simulated fuel assembly is plotted in Figure 4. The acceleration was filtered with a 300 Hz low pass Butterworth filter to eliminate high frequency content. It is common practice in testing to eliminate high frequency content recorded by transducers that are outside the range of interest to structural evaluations. The explicit finite element method can similarly calculate very high frequency content that is not relevant to structural analysis, so frequency band filtering is also very useful. This filtering action smooths the acceleration curves and eliminates short duration, high magnitude spikes. To the right of the chart is the legend, and a sketch that relates the lettered curves to fuel assembly locations in the basket. The difference between all fuel assembly responses is not large, but L is the location of maximum peak acceleration and G was the location of lowest peak acceleration.

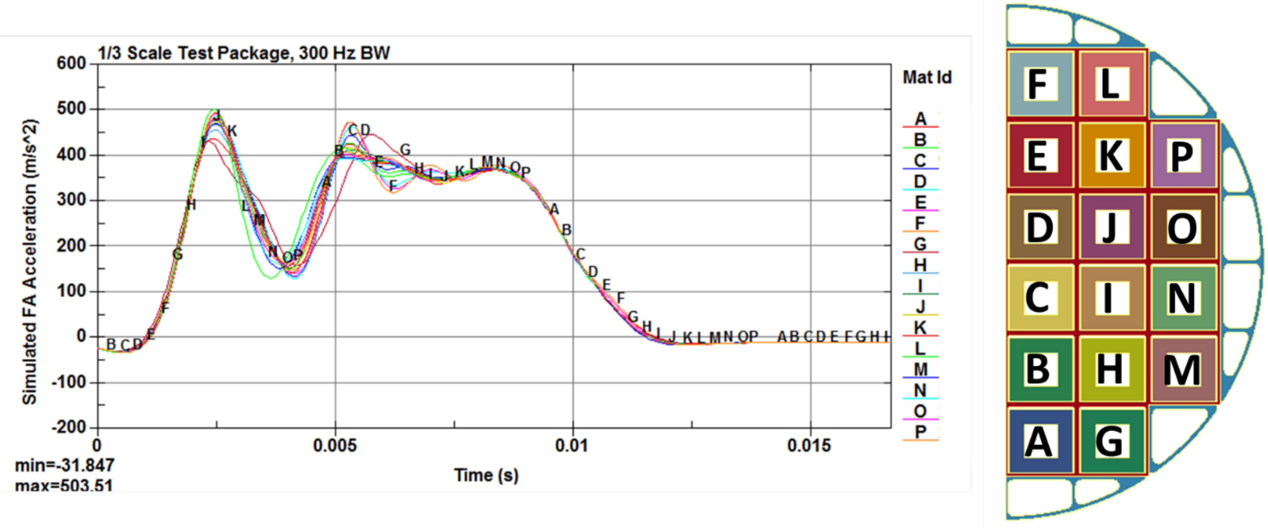

Figure 3: Preliminary 30 cm Drop Model Results

The model results were further evaluated and a prioritized list of instrumentation locations was created. Figure 5 shows a map of the instrumentation locations, with the lowest numbers being highest priority. The number of available data channels and accelerometers was not known at the time, and Sandia National Laboratories (SNL) staff made the final decision on instrumentation. Fuel assemblies 1, 2, 3, and 4 were the highest priority because they included the maximum and minimum peak accelerations from the test. Fuel assemblies 5, 6, and 7 were chosen because they matched locations from recent normal conditions of transportation testing [3, 4, 5]. Fuel assemblies 8 and 9 were selected because they were locations with relatively high peak acceleration at the second peak (around 0.006 s in Figure 4). Finally, fuel assemblies 10 and 11 were chosen to fill out a partial column. After the 11 selections were made for the reasons provided, there was no strong reason to suggest any more instrumentation locations.

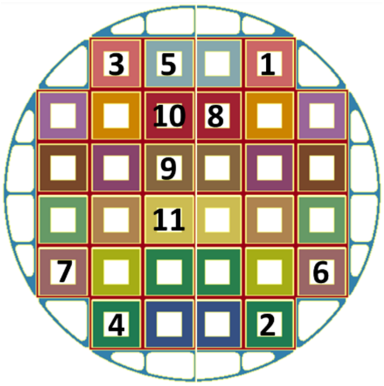

Figure 4: Instrumentation

Note that the instrumentation recommendations were made based on the orientation of the first drop test. Both tests used the same instrumentation plan for consistency.

30 CM DROP TEST 1

The full 3-D FEA model was used in a number of analyses that were performed ahead of the drop testing at BAM. One of the important unknowns in the model was the amount of gap that would occur between the simulated fuel assemblies and the basket structure at the moment of impact. When a package is at rest prior to the drop, it can be assumed that gravity forces the assemblies and the basket into intimate contact. But once the system is released, there is some question in the community whether that intimate contact will remain throughout impact, whether the bodies will separate during freefall due to the release of elastic energy, or if this question of physics is significant enough to have any practical effect on the loading conditions of SNF assemblies during package drop conditions.

In finite element models, an initial (nonzero) gap condition is desirable to ensure contact definitions work correctly. If finite element bodies start an analysis in an initial state of overlapping volumes (i.e., if the nodes on the surface of one body are initially penetrating the surface of another body) the calculation might not recognize contact between the bodies. Finite element codes like LS-DYNA have ways to deal with initial penetrations, but it is generally good FEA modeling practice to leave small gaps between bodies at the beginning of an analysis and the objects naturally make contact as the calculation progresses. This can be an issue in package impact load cases because they happen so quickly that a relatively small delay in contact can affect the transmission of forces throughout the system. Deciding how much gap is the right amount of gap is a challenge in FEA, but it is also a real and consequential phenomenon, and is one of the phenomena this test campaign was designed to study.

Prior to testing, the full 3-D finite element package model was calculated with two different gap conditions, a nominal condition (which was defined to have less than 1 mm of gap) and a zero gap condition (which was specially defined to have less than 0.001mm of gap). Figure 6 shows the package body rigid body acceleration in g (9.81 m/s^2) for the nominal gap case, the zero gap case, and the nominal case with a 300 Hz Butterworth low pass filter applied. The nominal case shows indications of secondary impacts (near 0.002 s) which correspond to interaction with the fuel assemblies (See Figure 7). The zero gap case eliminates secondary impact effects from the package body impact response, and very closely resembles the nominal case with the low pass frequency filter applied. It is common in package drop testing to apply a low pass frequency filter to test results to eliminate high frequency noise and establish a clean acceleration pulse shape. As demonstrated on the FEA results, the low pass filter also eliminates the influence of secondary impacts on the package response.

The average fuel assembly acceleration calculated in the nominal and zero gap FEA models are presented in Figure 7. The figure averages the finite element model calculated response of the 11 instrumented fuel assemblies. A significant difference in response is visible between the two cases, and that is due entirely to the initial gap condition. The nominal model case in Figure 7 shows a 0.002 s delay that corresponds to the acceleration dip shown in Figure 6. The peak acceleration is also affected in the cases, with the nominal gap case having a peak acceleration over 200 g, while the zero gap case has a peak below 50 g. The peak cask acceleration was predicted to be about 40 g, so even the zero gap case predicts fuel assembly accelerations to be 25% higher than the cask body peak acceleration.

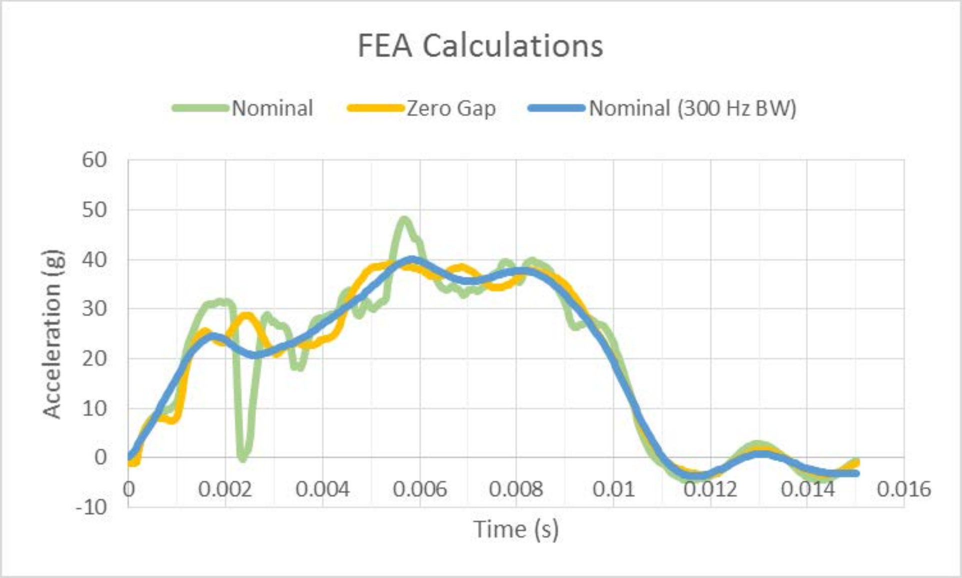

Figure 5: FEA Package Body Deceleration Pulse

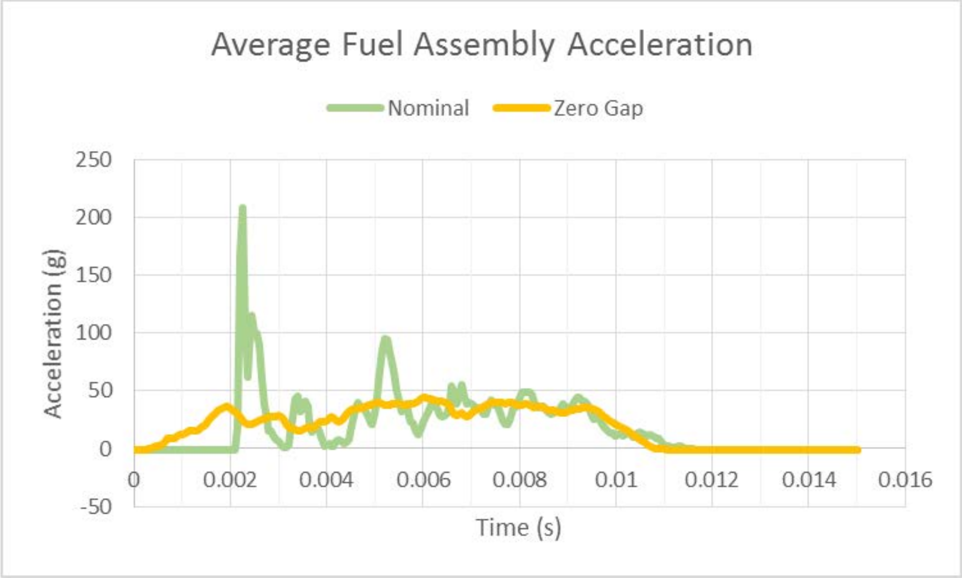

Figure 6: FEA Fuel Assembly Deceleration Pulse

Select test data from the first drop test are compared to FEA model results. A comparison of the nominal filtered acceleration to the average cask acceleration (average of 4 vertical accelerometer signals) is made in Figure 8. The test data is plotted with a time shift to approximately match the FEA model. The shock pulse from the model is approximately 0.003 s too short in duration, but otherwise has a similar shape. One explanation for this discrepancy is that FEA model represents a perfect horizontal impact, but the real test had a slight angle at impact. The accelerometer data shows a delay in impact between one end and the other of between 0.002 s and 0.003 s. This would naturally lengthen the duration of the impact pulse, as appears to be the case.

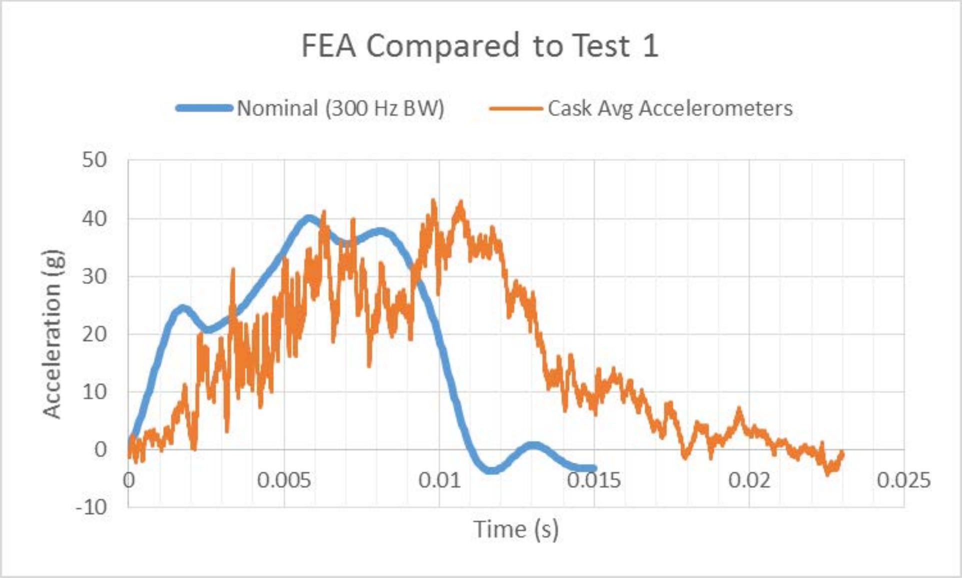

Figure 7: Package Body Deceleration, FEA Compared to Test Data

The average fuel assembly accelerations plotted in Figure 7 are repeated in Figure 9 for comparison against the test data. For the test data curve (Test 1), all vertical accelerometers on the 11 fuel assemblies are averaged together to show their composite behavior. The test data uses the same time shift as Figure 8 for consistency, but the model results would show a better agreement if the test data was shifted -0.003 s to account for the delay between both impact limiters making contact with the impact target. The test data shows an impact response behavior that is somewhat between the two FEA model results. There is a high frequency component similar to the nominal gap case, but the peaks are lower and closer in magnitude to the zero gap case.

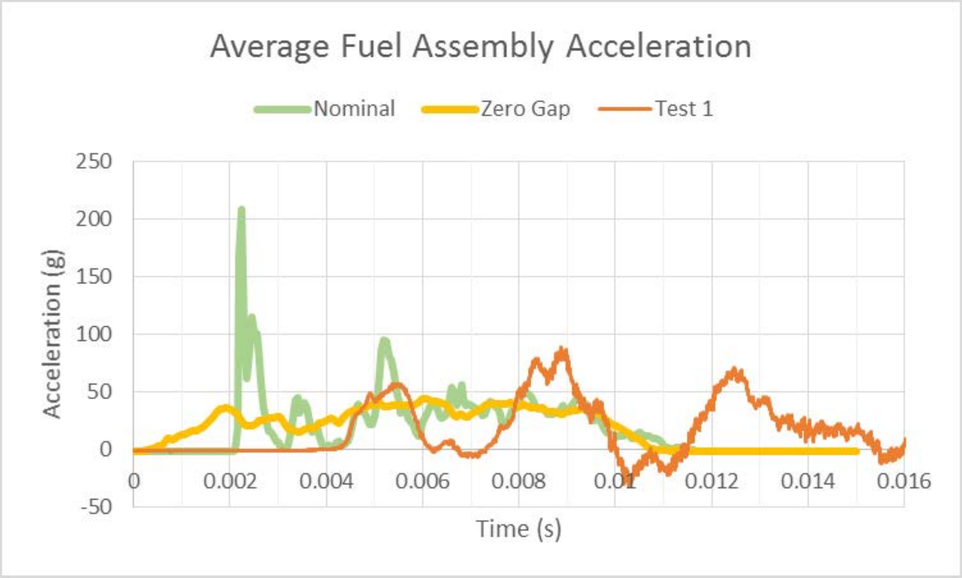

Figure 8: Fuel Assembly Deceleration, FEA Compared to Test Data

30 CM DROP TEST 2, 45-DEGREE ROTATATION

The second drop test was also a 30 cm horizontal drop, but in this case the package was rotated 45 degrees about its axis prior to impact. The motivation of the second test was to study the effect of the change in basket angle on the fuel assembly response. Figure 10 shows sketches of the two test configuration, and identifies the locations of instrumented fuel assemblies 1 and 2 for reference. (Rotate Figure 5 counterclockwise 45 degrees for the full map.) The exact same instrumentation was used in the second test, but in this configuration, none of the accelerometers pointed vertically. In locations with triaxial accelerometers, the Y and Z signals can be resolved to calculate the vertical component of acceleration. In locations without both of those channels, part of the vertical acceleration information is lost. The top 4 priority fuel assembly locations all had complete data channel sets, and they were located around the perimeter of the basket. This provided sufficient coverage to study the response of the fuel in the second drop case.

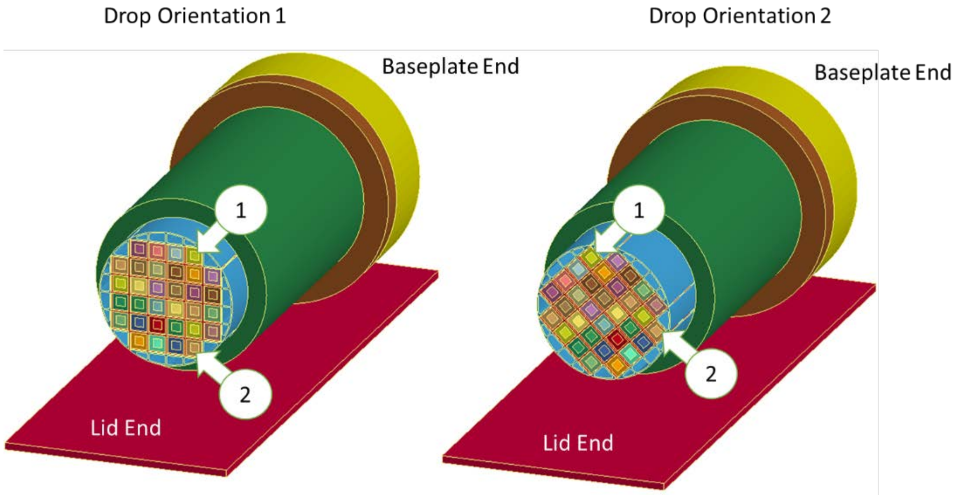

Figure 9: 30 cm Drop Test Sketches, Test 1 (Left), Test 2 (Right)

When the test data is appropriately resolved into the vertical direction, the Test 2 package body acceleration is very similar to Test 1. The peak average acceleration in Test 2 is 39 g, while the peak in Test 1 is 43 g, which is about a 10% difference. Qualitatively, the acceleration spikes appear lower in the Test 2 case, which suggests the secondary impacts of the fuel assemblies against the basket could be smaller in Test 2. The test data shows evidence of a similar delay in accelerometer response from one end to the other from a slightly off-horizontal impact orientation. The delay was about 0.003 s to 0.004 s, equal to or slightly greater than in Test 1.

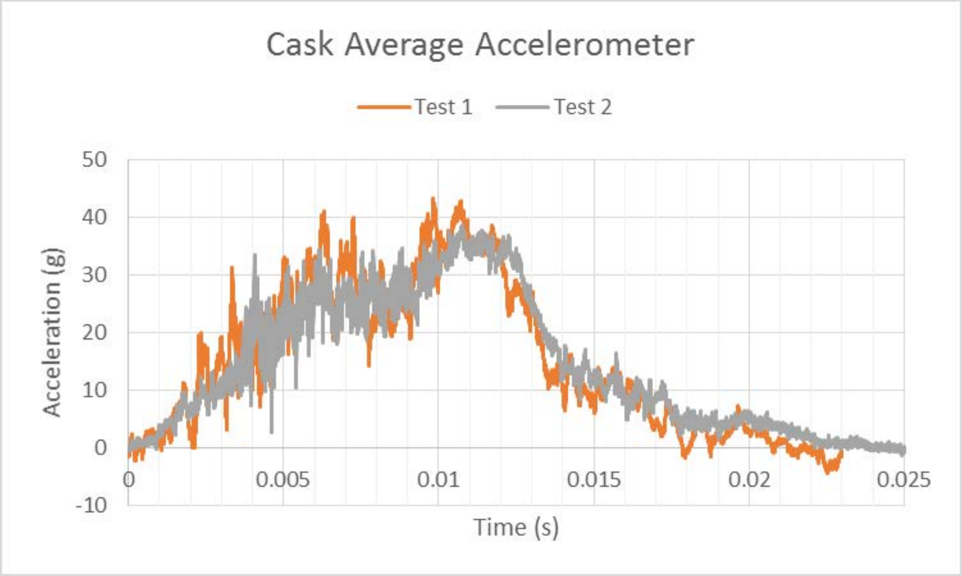

Figure 10: Package Body Test Data, Test 1 and Test 2

The average instrumented fuel assembly response is plotted in Figure 12 for a nominal gap FEA model, a zero gap FEA model, and the Test 2 accelerometer data for fuel assemblies 1, 2, 3, and 4 (where 2 triaxial accelerometers were on each assembly). Again, the FEA generally agrees with the test results.

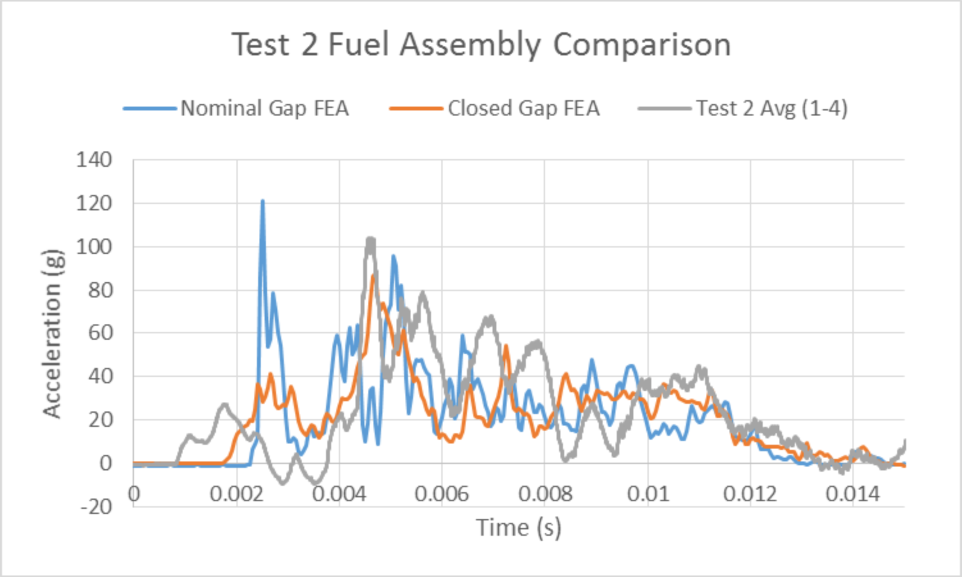

Figure 11: Fuel Assembly FEA Compared to Test 2 Data

CONCLUSIONS

This paper presented FEA and test data using average values to illustrate the trends and draw comparisons. Comparing individual data channels to FEA model results was too large a topic to fit into this paper, but this is included in the ongoing analysis work that is being done by PNNL. It is anticipated that the authors will complete a technical report on the ongoing work that will be available to the public near the end of 2019.

The contents of this paper provide a reasonable illustration that the FEA generally agrees with the test data. One difference in the model is a perfectly horizontal impact. It would not be difficult to adjust the model to achieve the same impact angle witnessed in testing.

The effect of gaps and secondary impacts remains an interest in this work, and future analyses will consider the effect of secondary impacts on fuel assembly components, including fuel rods. DOE is sponsoring this work to address the stress profiles knowledge gap identified in [6], and experimental testing and structural dynamics modeling are complimentary efforts that are being pursued to close that gap.

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