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Impact Limiter Computer Simulation and Verification by Drop Tests

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ABSTRACT

Impact limiters are often used to protect equipment by minimizing the load inflicted to the equipment due to an impact or fall. This paper presents a computer simulation of a simple and effective impact limiter used in a storage cask carrying a Multi-Purpose Canister (MPC) containing nuclear spent fuel assemblies and compares the analysis results with the actual drop test performed for the prototype of the impact limiter. The impact limiter consists of an array of stainless-steel tubes with small holes in each to define and accelerate the collapse of the tubes following an impact. The small holes drilled at the strategically picked location on the tube ensures a very uniform tube collapse pattern and thus a well-controlled overall impact limiter behavior. The numerical simulation is conducted with computer modeling in LS-DYNA with appropriate geometric parameters and material properties. The behavior of the impact limiter tubes is captured by the true stress true strain curve of the material. The numerical analysis reveals how the tubes collapse due to an impact from a drop accident and what the collapse pattern looks like. The prototype test is conducted to verify the accuracy of the computer model, and the collapse of the tubes is observed and recorded using a high-speed camera. Both the measured impact limiter deformation and impact acceleration match well with the predictions by the computer model. This simple impact limiter device is extremely effective in absorbing energy and the required design objective can be reliably confirmed by computer simulation.

Keywords: Impact Limiter, computer simulation, LS-DYNA, prototype testing, design analysis verification, drop accident, collapse pattern.

1. INTRODUCTION

The impact limiter is a device to minimize the impact load to an equipment due to a fall. The impact limiter is properly designed such that it absorbs maximum impact energy and decelerates the equipment so that the equipment lands softly. The example considered in this article is the transfer of a spent fuel canister to a storage cask, and during the transfer the postulated accident scenario is the fall of the canister within the cask due to the failure of the lifting equipment. The lifting equipment is designed with sufficient design margins so that its failure is highly unlikely. However, following the defense-in-depth principle a hypothetical fall is postulated and thus an impact limiter is needed to minimize the risk.

The impact limiter considered in this article is an array of tubes welded to a plate at the top and the bottom. During impact the tubes buckle and absorb energy. If the tubes are too soft, they may completely collapse, and the equipment experiences a hard landing. If the tubes are too hard, they may not absorb sufficient energy to provide the required deceleration. Therefore, the design of the impact limiter is very important, and a prototype test can provide the assurance of its intended function.

2. PHYSICAL DESCRIPTION OF THE IMPACT LIMITER

The impact limiter discussed in this article was used in a storage cask housing a spent fuel canister for spent fuel storage. During the transfer of the canister at the Cask Transfer Facility (CTF) there is a potential for dropping the canister into the cavity of the cask if the handling device is not single-failure proof. The canister drop height could be up to 5.4 meters during the transfer operation. As a defense-in-depth strategy, it is required to demonstrate that the potential canister drop accident would not result in unacceptable consequences. The storage cask discussed here is HI-STORM (Holtec International - Storage Module) and the canister is MPC; and both are of Holtec proprietary design [1]. The impact limiter is placed at the bottom of the HI-STORM cavity. This impact limiter is made of 22 stainless tubes with 8 inches (203.2 mm) diameter and 12.75 inches (323.9 mm) long, welded between wo plates as shown in Figure 1. There are 1.0-inch (25.4 mm) holes at the top and bottom end of the tubes.

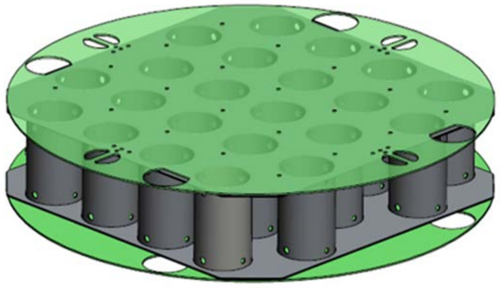

Figure 1: HI-TORM MPC Impact Limiter Design [1]

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3. FUNCTIONAL CHARACTERISTICS OF THE IMPACT LIMITER

The primary function of the impact limiter is to minimize the imparted load to MPC in case there is a vertical impact inside the HI-STORM cavity during the MPC transfer operation. The MPC enclosure vessel should not breach, resulting in radioactive release if the fuel assemblies stored inside the MPC are also damaged due to excessive impact loading. The MPC should remain in shape so that extraction from the storage cask is possible, if necessary. Therefore, the impact limiter tubes should be sufficiently long so that they do not go completely solid (bottom out) during the impact. The is critical to limiting the maximum acceleration of the MPC and thus to the structural integrity of the stored fuel assemblies. In addition, the impact limiter should be sufficiently stiff to carry the static load of the MPC under normal conditions of storage.

4. COMPUTER SIMULATION OF THE IMPACT LIMITER

The explicit finite element code LS-DYNA [2] is used to carry out the computer simulation of the impact limiter. Due to geometric symmetry in the designs of the MPC and the impact limiter, the MPC drop analysis model only considers a quarter of the impact limiter and the loaded MPC configuration. For simplicity and conservatism, the MPC contents are presented as a solid cylinder in the LS-DYNA model.

The accuracy of the computer simulation is essentially decided by how the crush material (i.e., the 316L stainless-steel tube) of the MPC impact limiter is modeled. For analyses involving large plastic deformation, which is expected to happen in the MPC impact limiter tubes, the true-stress-true-strain relationship of the material should be used to assure that reasonably accurate finite element analysis results can be obtained. Therefore, using tube vendor supplied material properties, a true-stress-true-strain curve is established to model the behavior of the MPC impact limiter tubes. The following provides the theoretic basis of constructing the true-stress-true-strain curve of a material.

Based on the stress and strain definitions, the following relationships between the true stress (σ) and the engineering stress (s) and between the true strain (ε_t) and the engineering strain (ε_e) are established for a tensile test specimen under uniaxial plastic deformation (i.e., before necking of the specimen or before the stress of the specimen reaching the maximum stress in the engineering stress-strain curve):

$$\sigma = s(1+\varepsilon_e) \tag{1}$$

$$\varepsilon_t = ln(1+\varepsilon_e) \tag{2}$$

The following power law relationship is widely used to approximate the flow curve of metallic materials subject to uniform plastic deformation.

$$\sigma = K{\varepsilon_t}^n \tag{3}$$

where n is the strain-hardening exponent and K is the strength coefficient. The actual true-stress-true-strain curve after necking is usually determined using the finite element method in conjunction with test data. For simplicity, Eq. (3) is extended to the entire flow curve so that n and K can be calculated based on material tensile test data.

For most metallic materials necking of the tensile test specimen begins at the maximum load and at a value of strain where the true stress equals the slope of the flow curve [3], i.e.,

$$\sigma_u = s_u(1+\varepsilon_{e\_u}) \tag{4}$$

$$\sigma_u = \left.\frac{d\sigma}{d\varepsilon_t}\right|_{\varepsilon_t=\varepsilon_{\mathrm{t\_u}}} \tag{5}$$

$$\sigma_u = K\varepsilon_{t\_u}^n \tag{3A}$$

where σ_u and ε_{t_u} denote the true stress and true strain at the maximum load during the tensile test of the material, while s_u and ε_{e_u} are the corresponding engineering stress and engineering strain at the maximum load.

The following relationship can be derived from the above three equations:

$$n = \varepsilon_{t\_u} \tag{6}$$

$$K = \frac{s_u e^n}{n^n} \tag{7}$$

where e = 2.718. Applying Eq. (3) again to the yielding point, we have:

$$K{\varepsilon_{t\_y}}^n = s_y\left(1+\frac{s_y}{E}\right), \text{ or}$$

$$K = \frac{s_y\left(1+\frac{s_y}{E}\right)}{\left(ln\left(1+\frac{s_y}{E}\right)\right)^n} \tag{8}$$

where s_y is the engineering yield stress and E is the Young's Modulus of the material. Eliminating K from Eqs. (7) and (8) results in the following equation:

$$s_u\left(\frac{e}{n}ln\left(1+\frac{s_y}{E}\right)\right)^n = s_y\left(1+\frac{s_y}{E}\right) \tag{9}$$

Using yield strength, ultimate strength, and Young's Modulus of the material, one can easily solve for the strain-hardening exponent n of the material from the above nonlinear equation using an engineering software tool such as Mathcad [4]. With the true fracture strain estimated per Eq. (10) below [5] based on the reduction of area data (q) from the tensile test, the complete true-stress-true-strain curve can be constructed using the linear relationship for the elastic region and Eq. (3) for the plastic region.

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$$\varepsilon_{t\_f} = ln\frac{1}{1-q} \qquad (10)$$

Validation of the above derived material flow curve has been performed by simulating tensile tests of different materials (including the 304 stainless steel) with satisfying accuracy in predicted elongation and reduction of area [7]. The true-stress-true-strain curve established for the impact limiter tube material is used in both the impact limiter design analysis and the simulation of the impact limiter prototype design drop tests.

5. ANALYTICAL RESULTS

The ultimate acceptance criterion for the MPC impact limiter design is that the containment boundary of the MPC enclosure vessel shall not breach due to the postulated drop accident. This criterion is used to establish a conservative plastic strain limit of 0.238 for the MPC enclosure vessel.

The impact limiter design analysis is conservatively performed by considering the maximum possible drop height at the CTF. As expected, the lower end of the MPC shell is structurally challenged most. As shown in Figure 2, the LS-DYNA simulation predicts minor plastic deformation in the lower portion of the MPC shell with a maximum plastic strain of 0.0066, which is significantly below the allowable value (0.238). Therefore, it is concluded that the impact limiter design satisfies the primary design requirement.

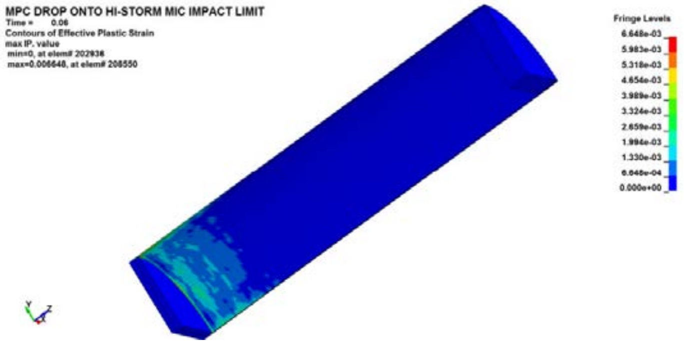

Figure 2: Maximum Plastic Strain of the MPC Enclosure Vessel

6. PROTOTYPE DESIGN FOR TESTS

A prototype of the impact limiter assembly (ILA) was tested at a load test facility for the purpose of verifying the performance of the impact limiter design using LS-DYNA. As shown in Figure 3, the ILA prototype has three crushable tubes of the same dimensions, spacings, and material as in the actual impact limiter design [1]. It is expected that the prototype should represent the characteristics of the MPC impact limiter.

The ILA prototype is attached to the bottom of the drop weight through clamping plates and attachment bolts. The 6,255 kg drop weight is a rectangular steel weldment of 1.0 m long, 1.0 m wide and 0.78 m thick. The drop weight designed for the drop test is intended to channel the same amount of impact energy to each impact limiter tube as the MPC in the postulated drop accident at the CTF. The displacement time history of the drop weight is captured by hi-speed cameras by monitoring the tracking markers attached to the drop weight side surfaces.

Figure 3: Impact limiter Prototype

7. DESCRIPTION OF DROP TEST PROGRAM

An outdoor test facility was selected for the test program. As shown in Figure 4, the impact limiter prototype drop test assembly is lifted by a 150-ton capacity crawler crane to the required drop height and kept level before it is released to initiate the drop test. The 700-ton impact target consists of 75 mm thick steel plates and a 6.1 m × 6.1 m × 7.1 m deep reinforced concrete block.

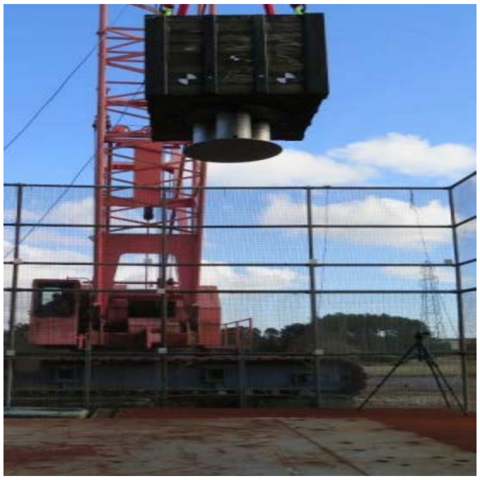

Figure 4: Assembled ILA Prototype/Drop Weight Pick Up by a Crawler Crane Before the Drop Test

Releasing the drop test assembly is realized by an electromechanical release system (Figure 5) for single point

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suspension of the drop test assembly. This method of suspension and release ensures that the test piece altitude is not affected by the release process.

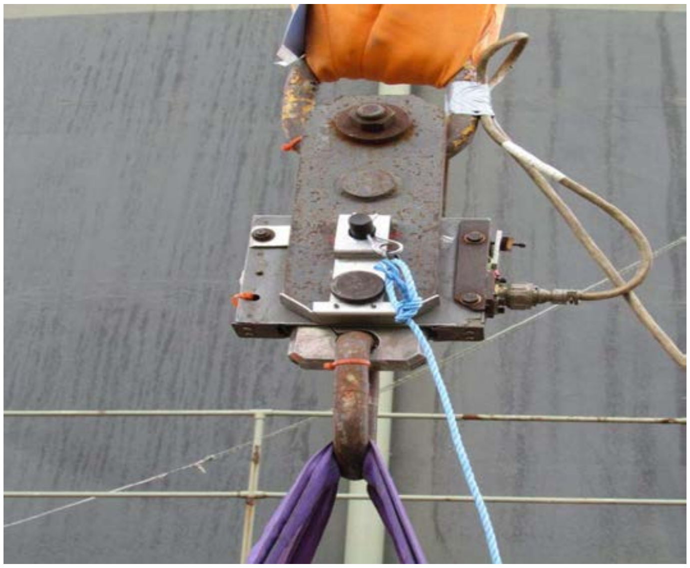

Figure 5: Electromagnetic Release Mechanism

The drop test program used three different drop heights to cover the potential fall of MPC: (1) 5.93 m in drop test 1; (2) 3.0 m in drop test 2; and (3) 4.05 m in drop test 3. High-speed cameras are used to record the drop weight vertical displacement time history, which provides the raw data to obtain the time histories of the drop weight's velocity and acceleration and the impact limiter tube deformation. No acclerometers were used in the tests. Figure 6 below shows the schematic of the drop test layout.

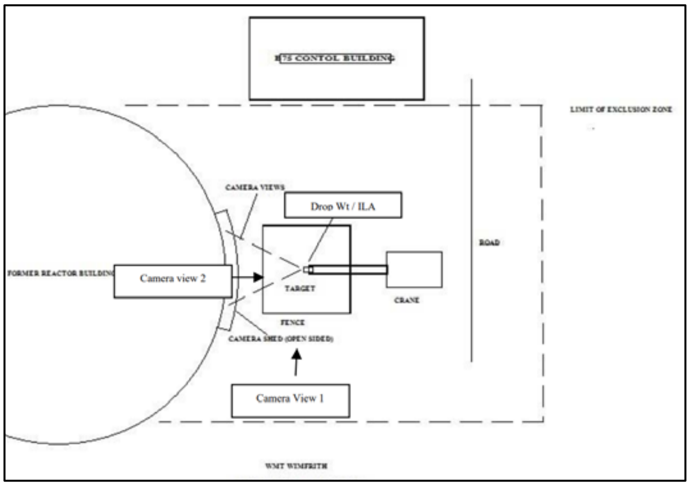

Figure 6: Drop Test Layout Schematic

Direct measurement of the impact limiter tube deformation was performed after the drop test. The post-test direct measurement is used to establish the crush depths of the impact limiter for various drop heights. In addition, it provides the basis to evaluate the tube deformation time history obtained from the hi-speed camera data, which is also used to derive the drop weight deceleration that governs the structural integrity of the MPC enclosure vessel.

7. ILLUSTRATION OF TEST RESULTS

Figure 7 shows the deformed shapes of the impact limiter tubes after the three drop tests. The ILA tube average deformation, obtained from the post-test direct measurement documented in the test report [6], is 10.14", 6.066" and 7.843" respectively for the three drop tests.

Figure 7: Deformed Shapes of Impact Limiter Tubes

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The above directly measured deformation results, which are also listed in Table 1 below, shall be considered accurate and reliable compared with the slightly larger deformation results indicated in the impact acceleration vs. tube deformation plots in Figure 8. These plots are created per the tabulated data of the drop weight displacement and acceleration time histories (also documented in the same test report [6]), which were obtained by processing the drop weight displacement time histories mesured by the camera. The discrepancy is very likely caused by a combination of the following effects: (1) There might be a relative vertical displacement between impacted ground surface and the camera supporting surface during the drop test, which would lead to an increased vertical displacement of drop weight (and thus increased impact limiter tube deformation) observed by the camera. This is consistent with the observation that the difference increases with the drop height, i.e., the deformation differences are about 16 mm, 26 mm and 34 mm for the drop heights of 3.0 m, 4.05 m and 5.93 m, respectively. (2) The displacement time history recorded by the hi-speed camera was filtered to remove spurious hi-frequency noises, and the filtering process might distort the initial contact time instant of the impact leading to an artificially prolonged impact duration and thus an increased the impact limiter tube deformation which is reflected in the impact acceleration vs tube deformation plots in Figure 8.

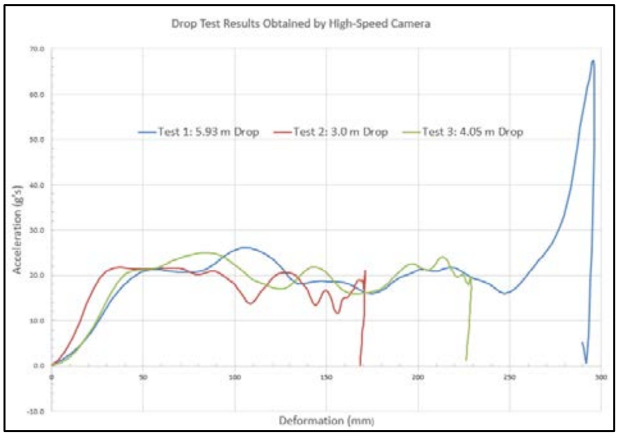

Figure 8: Impact Limiter Acceleration vs Deformation Test Results Obtained from Hi-Speed Camera

As shown in Figure 8, the acceleration history of the drop weight is relatively flat, narrowly varying about a mean value of slightly over 20 g's in all three drop tests except for the large acceleration spike near the end of the 5.93 m drop test. The large acceleration spike indicates that the impact limiter bottoms out.

8. COMPARISON OF THE ANALYTICAL AND EXPERIMENTAL RESULTS

The LS-DYNA simulations performed for the three drop tests predict similar ILA deformations. As shown in Table 1, the difference between LS-DYNA prediction and measurement is not significant in all drop tests. The maximum percentage difference shown in Table 1 is very much like that observed in the 304 stainless steel tensile test simulations [7]. Note that tensile test simulations of the other two materials yielded much better accuracy than the more ductile stainless steel.

Table 1: Comparison of Impact Limiter Tube Deformation Between Direct Measurement and LS-DYNA Simulation:

Drop Test	Post-Test Measurement (in/mm)	LS-DYNA Prediction (in/mm)	Difference
1. 5.93 m drop	10.14/257.6	10.9/276.9	7.5%
2. 3.0 m drop	6.066/154.1	5.42/137.7	10.6%
3. 4.05 m drop	7.843/199.2	7.33/186.2	6.3%

The following three figures show the drop weight rigid body acceleration vs. tube deformation predicted by LS-DYNA simulations of the three drop tests. To make a fair comparison with the drop test results, the LS-DYNA acceleration and deformation time history results are output at the same time interval as that used in the provided test result data.

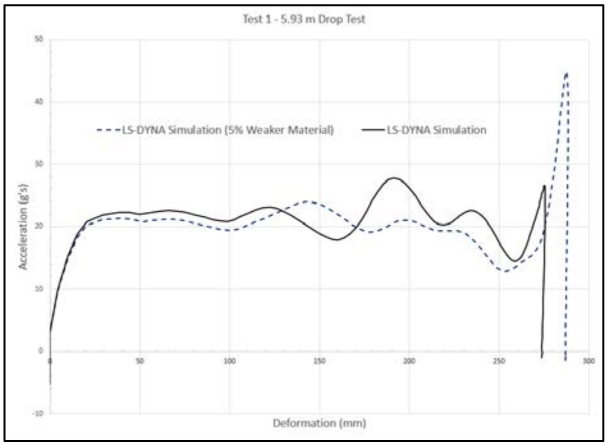

Figure 9: Impact Acceleration vs ILA Tube Deformation (LS-DYNA Simulation of Test 1)

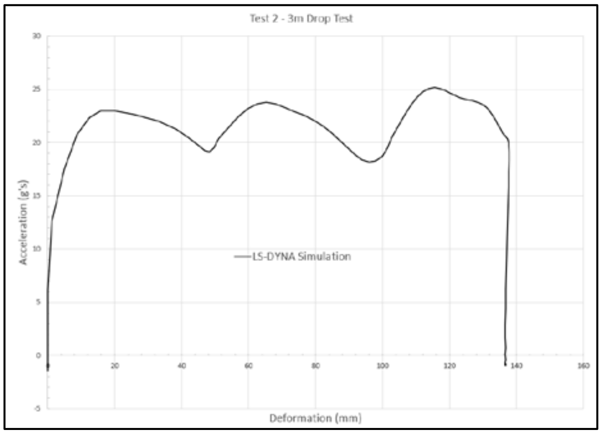

Figure 10: Impact Acceleration vs ILA Tube Deformation (LS-DYNA Simulation of Test 2)

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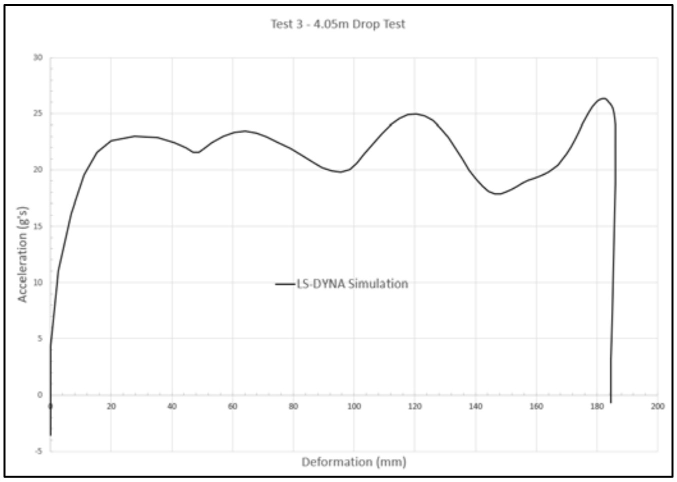

Figure 11: Impact Acceleration vs ILA Tube Deformation (LS-DYNA Simulation of Test 3)

LS-DYNA simulations of the three drop tests all predict relatively flat impact decelerations oscillating around 20 g's, similar to those obtained from the test results (see Figure 8). The only significant difference is that the numerical simulation of the 5.95 m drop test (see the solid line in Figure 9) fails to predict the acceleration spike near the end of the tube deformation as indicated in Figure 8. As discussed in Section 4, the power law flow curve is used to approximate the actual true-stress-true-strain curve of the material. To have an idea of how significant the material flow curve approximation error might be, an additional LS-DYNA simulation is performed for the 5.95 m drop test by lowering the material stress strain curve of the tube material by 5%. As shown by the dashed line in Figure 9, the slightly adjusted tube material model can capture the acceleration spike near the end of the impact.

It should be noted that the maximum MPC drop height at the CTF is smaller than the drop height considered in drop test 1. Figure 12 plots the relationship between the directly measured tube deformation and the drop height. For the maximum possible MPC drop height of 5.4 m during MPC transfer operation at the CTF, the tube deformation is expected to be less than 240 mm by interpolation of the data in Figure 12. Both the test results and the LS-DYNA simulations confirm that a large acceleration spike would not happen if the tube deformation does not exceed 240 mm. Therefore, ILA prototype tests and the corresponding LS-DYNA simulation verify that the MPC impact limiter will not bottom out in an MPC drop accident. In addition, the level of impact accelerations observed from the prototype tests and the numerical simulations is not sufficiently high to compromise the structural integrity of the spent fuel assemblies stored in the MPC.

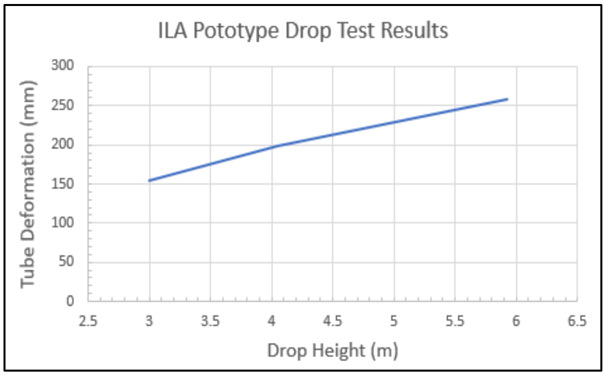

Figure 12: ILA Tube Deformation vs Drop Height

Finally, LS-DYNA simulations of the three drop tests predict a similar patten of tube deformation (see Figure 13) to that observed in the drop tests. Namely, major tube plastic deformation starts from the lower end of the impact limiter and significant local buckling typically occurs at the same vertical location of the tube to form a stiff triangle.

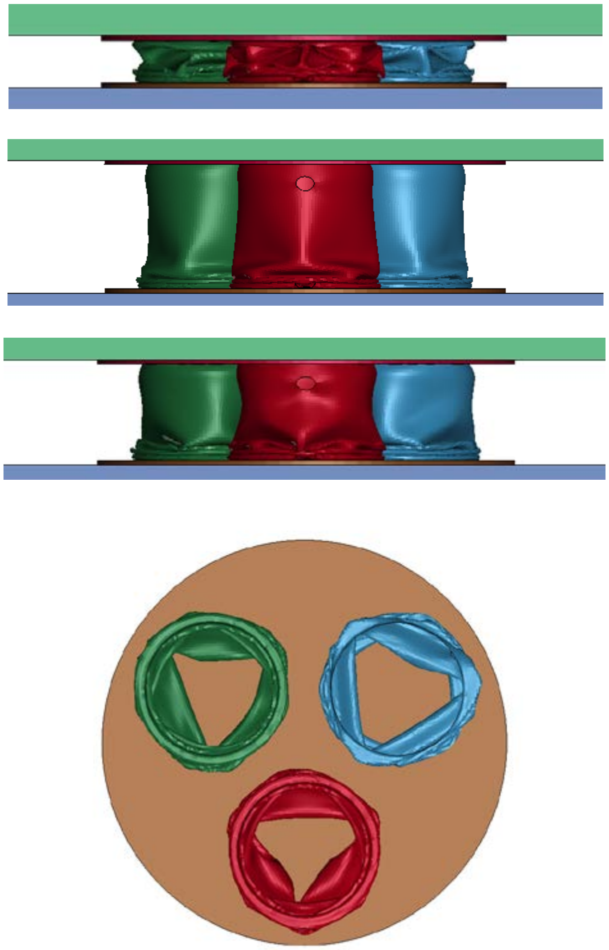

Figure 13: ILA Tube Deformation Predicted by LS-DYNA

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9. CONCLUSION

The performance of the impact limiter simulated on LS-DYNA compares well with the results of the prototype tests even with significant plastic deformation and the results can be used in the design of equipment. By using the true-stress-true-strain curve constructed solely based on the readily available material tensile test data, sufficiently good correlations between the test results and the corresponding numerical analysis results can be achieved. The differences in the test results and the numerical analysis can be attributed to the variation of the material properties of the impact limiter material from the ideal values, test conditions, as well as simplifying assumptions involved in the analysis. However, it can be concluded that the design of the impact limiter developed based on this numerical analysis method is sufficiently accurate for the application.

10. REFERENCES

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