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Title: ANSYS Explicit Modeling for Prospective SAVY Designs and Worst Case Impact Orientation during Drop

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Introduction

A preliminary experimental drop test of a new 5.5 gallon SAVY-4000 container at a 12 ft height resulted in an impact angle of approximately 26 degrees and significant deformation of the locking ring and locking collar. Subsequently, the SAVY failed leak tests following the drop test. Based on previous analyses on SAVY containers, the primary modes of failure were determined to be vertical drops directly over the lid for the larger diameter sizes. The tests were initially bounded by the 45 degree impact angle. It was necessary to determine if a new bounding case existed at or near an impact angle of 26 degrees. In addition to characterizing the drop angle, modifications to the existing SAVY components were applied and analyzed to determine if container deformations could be minimized. Figure 1 includes the primary drop configurations investigated. A parametric study was conducted to determine the sensitivity of lid and collar deformation as a function of impact angle.

Figure 1. Drop configurations for containers (NFT, 2017).

Methods and Simulation

Due to the nature of the high strain and stress that occur over a small time period during impact, the Explicit solver was used to determine the deformation occurring at the interface between the lid and the collar. Figure 2 shows the arrangement of the SAVY container, its proximity to the Base Plate, and the internal payload. Sensitivity of drop angle was investigated through rotating the Base Plate about the Point of Impact, as indicated in Figure 2. Impact velocity associated with a 12 ft drop and gravity was oriented perpendicularly to the Base Plate. Angles of 0°, 15°, 26°, 45°, 75°, and 89° were investigated. The angle of 89 was selected so that the resulting loading on the locking ring at the top of the SAVY

would not be distributed over the entire surface. By modeling 89° , the Case F from Figure 1 would be captured with a realistic impact load applied to the vertically oriented SAVY. Two additional configurations were investigated to determine quantitative estimates of reduction in deflections along the lid and collar. The two alterations investigated are shown in Figure 3. The first was adding webbing along either side of the locking ring. The second was providing additional, webbed material underneath the lid to provide structural reinforcement.

All components of the SAVY-4000 were treated as perfectly bonded parts, with the exception of the Handle and the bolts associated with the handle. The bolts surfaces were treated as bonded surfaces to the locking ring while the Handle was free to rotate about the bolts with a friction coefficient of 0.15. Applying the friction coefficient to the handle allowed for it to rotate and provided a more accurate mass representation than had the Handle been rigidly bonded to the bolts. The SAVY was treated as Stainless Steel (SS) 304 with the exception of the Locking Ring and the inner Payload. The actual SAVY is SS 316L; however, nonlinear properties for SS 304 are already preprogrammed into ANSYS Explicit and the differences between the two materials and their behavior under high strain are second order when pertaining to the error. The Locking Ring was treated as Aluminum 7075 and the inner Payload was treated as tungsten. Nonlinearity resulting from materials were captured primarily through the Aluminum 7075, the Stainless Steel 304, and the Tungsten. Uniaxial test data capturing the nonlinear stress-strain behavior for Aluminum 7075 is provided in Table 1.

Figure 2. Setup for SAVY-4000 ANSYS Explicit Simulations.

The Inner Payload was simplified to a cylindrical mass representative of the 16 kg of Tungsten shot that was utilized in the experiments (NFT, 2017). The density of the Tungsten was set to 19300 kg/m³. The purpose of Tungsten inclusion was to accurately capture the mass of the system and the interactions occurring within the SAVY-4000. Stress-strain behavior of the Stainless Steel 304 was simplified to a bimodal characterization with both linear and nonlinear regimes being represented. The Young's Modulus was assigned to a value of 2.00×10¹¹ Pa. Yield strength was set to 2.50×10⁸ Pa and the ultimate strength was treated as 4.60×10⁸ Pa. Poisson's ration was set to 0.30.

Table 1. Aluminum 7075 Uniaxial Test Data Applied to Nonlinear Material Model

Strain m m ⁻¹	Stress Pa	Strain m m ⁻¹	Stress Pa
0	4.63E+08	7.78E-02	5.62E+08
1.81E-03	4.72E+08	8.08E-02	5.63E+08
3.56E-03	4.80E+08	8.37E-02	5.63E+08
5.36E-03	4.89E+08	8.67E-02	5.64E+08
7.20E-03	4.97E+08	8.97E-02	5.64E+08
9.19E-03	5.04E+08	9.27E-02	5.65E+08
1.14E-02	5.11E+08	9.57E-02	5.65E+08
1.39E-02	5.16E+08	9.87E-02	5.65E+08
1.66E-02	5.20E+08	0.10169	5.66E+08
1.94E-02	5.24E+08	0.10469	5.66E+08
2.22E-02	5.27E+08	0.10768	5.66E+08
2.51E-02	5.30E+08	0.11067	5.66E+08
2.79E-02	5.33E+08	0.11366	5.65E+08
3.08E-02	5.36E+08	0.11665	5.64E+08
3.37E-02	5.38E+08	0.11964	5.63E+08
3.66E-02	5.40E+08	0.12262	5.62E+08
3.95E-02	5.42E+08	0.12561	5.60E+08
4.24E-02	5.44E+08	0.12859	5.58E+08
4.54E-02	5.46E+08	0.13156	5.55E+08
4.83E-02	5.47E+08	0.1345	5.53E+08
5.13E-02	5.49E+08	0.13736	5.50E+08
5.42E-02	5.51E+08	0.14014	5.46E+08
5.71E-02	5.52E+08	0.14291	5.43E+08
6.01E-02	5.54E+08	0.14579	5.38E+08
6.30E-02	5.56E+08	0.14885	5.33E+08
6.60E-02	5.57E+08	0.15188	5.27E+08
6.89E-02	5.59E+08	0.15453	5.21E+08
7.19E-02	5.60E+08	0.15645	5.17E+08
7.48E-02	5.61E+08

Figure 3. SAVY with modified locking ring (left) and lid (right) geometries.

The minimum grid size existing within the lid, locking ring, and collar is approximately 0.003 m. Time step selection providing a CFL number (Courant, 1967) of one is required to provide numerical stability. Based on the velocity observed by the SAVY and the characteristic cell length based on the minimum grid spacing applied, a time step between approximately 8.506×10^{-9} s and 9.981×10^{-9} s was applied. An end time of 0.0015 s was necessary for a full impact of the SAVY at the prescribed velocity. At these time steps and set end time, approximately 1.57×10^5 and 1.76×10^5 cycles were necessary for a final, converged solution. Figure 4 shows the gridding arrangement utilized for the original configuration investigating the drop angle sensitivity. For each configuration a total grid of approximately 2.6 million cells was applied with grid density emphasized within the lid and collar, particularly near the point of impact. Lower order, two-dimensional shell elements were applied to the payload body and the cylindrical volume of the SAVY-4000 body to reduce computation time. Using 24 processors, the solution was acquired between one and two days. The total energy in the system is on the order of 10^3 Joules while the calculated energy error was confined to an order of magnitude of ≤ 1 Joules.

To replicate the impact velocity during a 12 ft drop, the following equation was applied to determine velocity based on perfect potential to kinetic energy conversion:

$$v_{imp} = \sqrt{2gh}$$

Where the velocity at impact is v_{imp} , g is gravity, and h is the initial height. For a 12 ft drop, the impact velocity applied to all SAVY-4000 and Payload bodies was 8.47 m/s.

Figure 4. Grid used for explicit analysis.

Results and Discussion

Figures 5 through 7 show the deformation values in the x-direction and the z-direction at a 26° impact angle for each design iteration. For the original configuration, in Figure 5, there was a peak deformation of approximately -0.0146 in. near the point of impact. The z-direction deformation is slightly offset from the point of impact. The magnitude of the peak deformations in both the x-direction and the z-direction result in a radial peak deformation slightly offset from the point of impact. This location shows qualitative agreement with the experimental results presented by NFT (2017). When the modified Locking Ring was implemented, similar excessive deformations were present within the collar. However, the new design feature changed the characteristics of the deformation and changed the direction at which the deformation occurred. It should be noted that in terms of deformation alone, there were minimal improvements when implementing the modified Locking Ring. In Figure 7, when the new Locking Ring and the new Lid design were both incorporated, the deformation near the point of impact in the x-direction was reduced to 0.0064 in. This is a substantial decrease compared to that observed in Figure 5. During the initial characterization of the impact angle, it was observed that as the payload struck the inside of the Lid that the Lid itself vibrated. The vibration observed is the primary cause of the high deformation values observed for the original design. Implementing both the new Locking Ring and the new Lid geometry both reduce the maximum deformation from 0.01131 in to 0.0065 within the collar along the surface of interest. The Lid sees a reduction from 0.0183 in down to 0.0064 in. The significant reduction in deformation observed in the Lid is a result of that axisymmetric addition of the ribbing on the underside of the Lid, shown in Figure 3.

Figure 5. Deformation (in.) in the Collar for the original configuration.

Figure 6. Deformation (in.) in the Collar for the configuration with the modified Locking Ring.

Figure 7. Deformation (in.) in the Collar for the configuration with modified Locking Ring and Lid.

The deformations observed in the Lid, shown in Figures 8 and 9, showed no changes in deformation direction even with new geometries implemented and new Lid-Payload interactions. The robust ribbing added to the underside of the Lid negates both the variability and dependency on the impact angle of the SAVY and the Payload contact within the SAVY. Tables 2 and 3 show the tabulated values for both the variable impact angles of the SAVY investigated, as well as the three design configurations considered. Table 2 indicates that the 26° impact angle was not the worst case scenario for the SAVY. Predictions produced reaffirm the already known worst case used in design and analysis of the system: that where the center of gravity (CG) is over the top corner (Case A in Figure 1), corresponding to a 45° impact angle.

Figure 8. Deformation (in.) in the Collar for the original configuration.

Figure 9. Deformation (in.) in the Collar for the configuration with modified Locking Ring and Lid.

Table 2. Deformation results based on angle of impact for original design

Angle	X-Direction Deformation Magnitudes Near Point of Impact (in)	
	Lid	Collar
0°	0.0357	0.0276
15°	0.0243	0.0151
26°	0.0183	0.0146
45°	0.0236	0.0563
75°	0.0175	0.0488
89°	0.0171	0.0331

The reduction in progressive design iterations investigated in Table 3 shows that the modified Lid geometry significantly reduces the amount of deflection observed along the surface of interest. The modified Locking Ring alone improved the rigidity of the Lid within the assembly, but also resulted in increased deflection along the Collar. Additionally, the modified Locking Ring is not axisymmetric and is heavily dependent on orientation at which the SAVY strikes the ground. The modified Lid provides a 65.0% reduction in the deformation. In future design iterations, when pertaining to reduction of deformation along the Lid, improving the rigidity and minimizing the vibration experienced by the Lid should be the primary focus.

Table 3. Deformation results for each design iteration.

Design Iteration	X-Direction Deformation Magnitudes Near Point of Impact (in)	
	Lid	Collar
Original, No Modifications	0.0183	0.0146
Modified Locking Ring	0.0109	0.0162
Modified Lid and Locking Ring	0.0064	0.0076

Conclusions

Explicit analyses were conducted to capture the highly nonlinear stress-strain behavior resulting when impact loads are applied to a SAVY-4000 container. Simulations were conducted with an impact velocity magnitude of 8.47 m/s to reflect a 12 ft drop, at variable impact angles ranging from 0° to 89°, resulting in deformations up to 0.0357 in. for the Lid and 0.0563 in. for the Collar. The parameter study indicated that the worst case loading was still the CG over top corner case that was previously used in other engineering analyses and safety analyses for SAVY containers. Results were highly dependent on the interaction between the Payload and the inside of the SAVY. Significant vibrations were observed along the Lid during impacts.

Two alternative designs were investigated to determine if the deformation values could be reduced with minor geometric alterations to components. The first design iteration consisted of a modified Locking Ring. Under the same loading conditions, at a 26° impact angle, there was a 40.4% reduction in the maximum deflection near the point of impact. The second iteration provided a modified Lid with ribbed material on the underside of the Lid geometry. The modified Lid and Locking Ring produced a 65.0% reduction in the deformation. The modified Lid significantly reduced the vibrations and high, transient deflections occurring along the Lid during impact.

References

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