

Orion Parachute Riser Cutter Development

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Abstract

This paper presents the tests and analytical approach used on the development of a steel riser cutter for the CEV Parachute Assembly System (CPAS) used on the Orion crew module. Figure 1 shows the riser cutter and the steel riser bundle which consists of six individual cables. Due to the highly compressed schedule, initial unavailability of the riser material and the Orion Forward Bay mechanical constraints, JSC primarily relied on a combination of internal ballistics analysis and LS-DYNA simulation for this project.

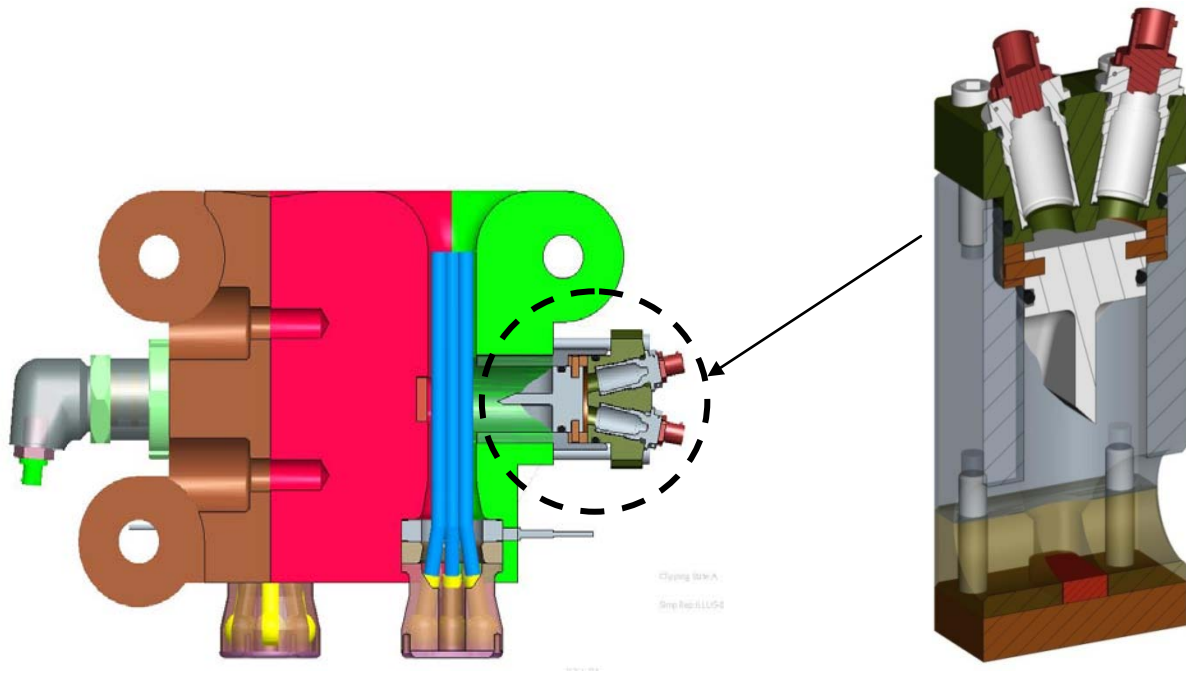


Figure 1 : CPAS Riser Cutter

Various one dimensional internal ballistics codes that use standard equation of state and conservation of energy have commonly used in the development of CAD devices for initial first order estimates and as an enhancement to the test program. While these codes are very accurate for propellant performance

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prediction, they usually lack a fully defined kinematic model for dynamic predictions. A simple piston device can easily and accurately be modeled using an equation of motion. However, the accuracy of analytical models is greatly reduced on more complicated devices with complex external loads, nonlinear trajectories or unique unlocking features.

A 3D finite element model of CAD device with all critical features included can vastly improve the analytical ballistic predictions when it is used as a supplement to the ballistic code. During this project, LS-DYNA structural 3D model was used to predict the riser resisting load that was needed for the ballistic code. A Lagrangian model with eroding elements shown in Figure 2 was used for the blade, steel riser and the anvil. The riser material failure strain was fine tuned by matching the dent depth on the anvil with the actual test data. LS-DYNA model was also utilized to optimize the blade tip design for the most efficient cut.

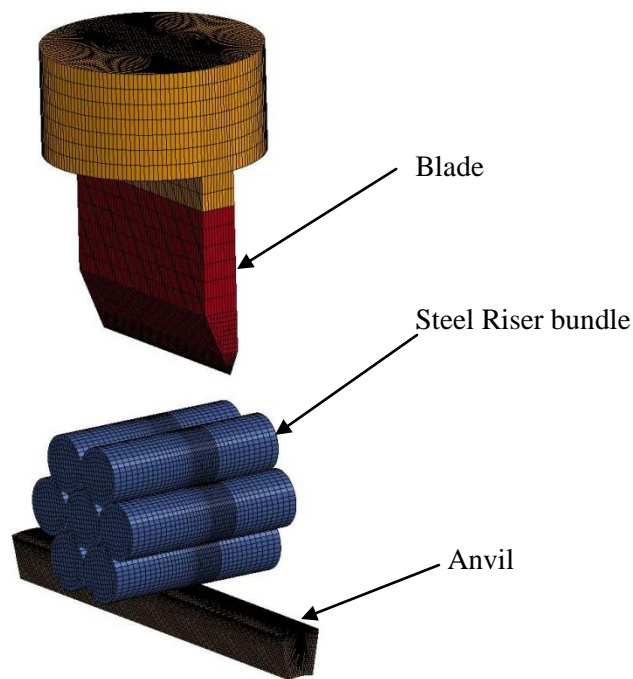


Figure 2: Riser Cutter LS-DYNA Model

In parallel, the propellant type and the amount were determined by using CADPROG internal ballistics code. Initial test results showed a good match with LS-DYNA and CADPROG simulations.

Final paper will present a detailed roadmap from initial ballistic modeling and LS-DYNA simulation to the performance testing. Blade shape optimization study will also be presented.

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The parachute assembly is an integral part of the Orion crew module Landing and Recovery System (LRS) and consists of two drogue and three main parachutes. A pyrotechnic cutter is used to sever the drogue parachute riser lines during the terminal descent phase of the mission and the main parachute riser lines shortly after splashdown. An Orion vehicle configuration change required a change on riser material and created an immediate need for a steel riser cutter to be used in the parachute drop tests. The development of this riser cutter with an extremely tight schedule required an accurate analytical and simulation approach to meet the delivery date. An internal ballistic model and a structural explicit hydrodynamic simulation were developed to support the Orion parachute assembly test program.

Nomenclature

A_p	= piston diameter
B	= burn rate coefficient
C	= propellant mass
C_v	= specific heat at constant volume
E_{HL}	= heat loss
F	= impetus
F_{EXT}	= external force (cable resisting load)
F_f	= friction force
m	= piston mass
m_p	= mass of propellant gas produced
n	= burn rate exponent
P_C	= chamber pressure
r	= propellant burn rate
S	= propellant surface area
T	= gas temperature
T_o	= isochoric flame temperature
V_C	= initial chamber volume
x	= stroke
ρ	= propellant mass density
η	= co-volume

I. Introduction

Orion parachute assembly riser cutter is a pyrotechnically actuated guillotine that is used to sever the drogue and main parachute steel risers during final descent and landing phases. The riser lines consist of a bundle of six steel cables with a tensile load capacity of 16,000 pounds for each cable. The cutter assembly requires dual pyrotechnic cartridges for redundancy; each initiated by a NASA Standard Initiator (NSI).

The focus of the present work was to perform a detailed analytical assessment of the cutter design, and test and manufacture the test hardware for the Parachute Test Vehicle (PTV) drop tests. Figure 1 depicts the primary

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components of the riser cutter. The cutter consists of a steel blade, piston retainer, cutter housing, an anvil, shear pins and dual cartridges. Upon receiving a firing signal, NSI's ignite the cartridge assemblies. The blade which is held in place with shear pins starts to stroke as soon as the cartridge output pressure shears the pins. After approximately half an inch of stroke, the blade impacts the cable bundle and severs it. After the complete severance of the riser bundle, blade penetrates into the steel anvil and finishes its stroke. One of the major factors driving the cutter design was that the cutter must demonstrate performance margin by cutting the target with a single cartridge loaded with a reduced amount of propellant load (85%) and show no structural yielding when cutting with both cartridges loaded at 115%. Furthermore, the cutter assembly is required to maintain structural integrity when tested in a locked-shut condition with dual nominally loaded cartridges.

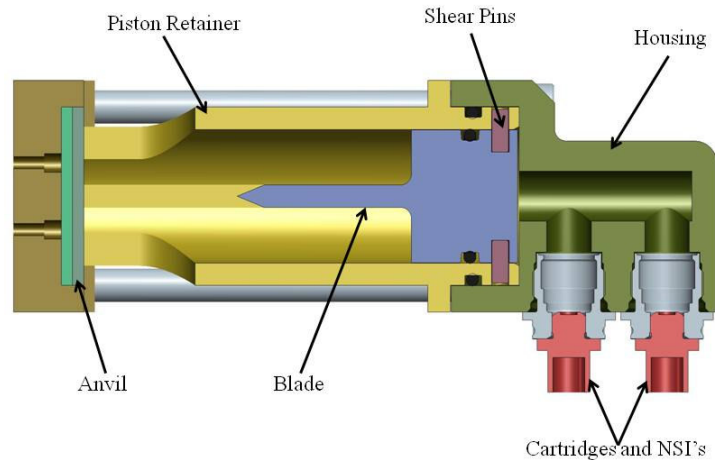


Figure 1. Riser Cutter Components

The flowerpot is a single structural element that retains each riser via a “puck”. The puck captures the cables individually using swaged fittings. The flowerpot also serves as a guide to channel the riser through the cutter. The risers emerge from the guides and spread out to their respective parachutes (hence the name flower pot). Figure 2 shows the interface between the flowerpot and the cutter assembly.

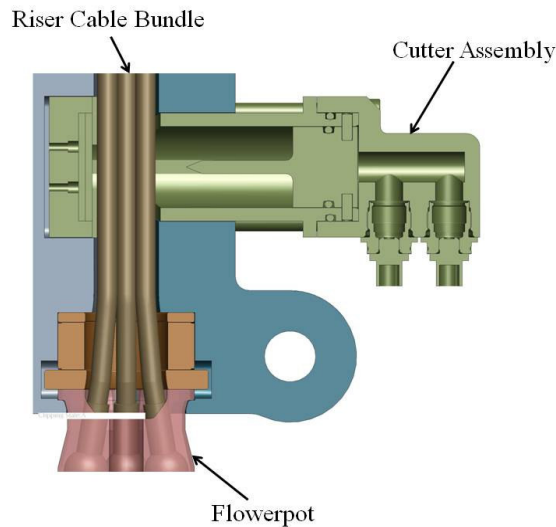


Figure 2. Riser Cutter / Flowerpot Interface

At the start of the development effort, the flowerpot was still in design and integrated cutter envelope was not determined. Some dimensions were known but the effort was fluid and would force the cutter envelope to move. This forced the initial efforts to analyze the blade and target in order to get estimates on energy losses due to wear on blade leading edge. Seven strands of a substitute cable were analyzed in place of six flight cables to account for work hardening and strength deficiencies compared to the actual flight cable. Variations in blade edge and shape were analyzed. Unfortunately the most efficient blade was not used because it drove and increased stroke and envelope constraints could not be maintained. The cutter envelope required a cutter outer diameter that was relatively small. The project imposed a standalone cutter which could not utilize the flowerpot structure and effectively reduced the envelope even more. After the blade configuration was established, the piston and blade standoff could be baselined. The decision was made to leverage the existing parachute textile strap cutter design parameters (i.e. clearances, seals, test hardware). The use of a common and available propellant was required. This enabled the analysis methods used to provide a quick estimate for propellant quantities prior to testing.

JSC primarily relied on a combination of internal ballistics analysis and nonlinear explicit finite elements simulation for this project. These two mathematical approaches were used in tandem to establish the optimum pyrotechnic charge while accurately predicting the resisting shear loads, the blade performance and the anvil configuration.

CADPROG internal ballistics code was used to simulate the ballistic performance of the riser cutter. While CADPROG is very accurate for propellant performance predictions, it requires external load input either from test data or a high fidelity structural simulation code such as LS-DYNA. For the study presented here, LS-DYNA structural model was used to predict the riser resisting loads that were needed for the ballistic analysis. LS-DYNA model was also used to optimize the blade shape and the material and to estimate the reaction loads that the vehicle encounters.

II. Internal Ballistic Analysis

CADPROG was originally developed by NSWC Indian Head Division and recently updated by JSC to enhance the heat loss and external loading modules. It is a one-dimensional internal ballistics code that uses time-dependent nonlinear equations of gas dynamics. The governing equations that need to be solved consist of conservation of energy and mass as well as the Nobel-Abel equation of state.

The conservation of energy for stroking pyrotechnic devices such as a guillotine cutter is as follows:

$$c_v \frac{d(m_p T)}{dt} = c_v T_0 \frac{dm_p}{dt} - A_p P_c \frac{dx}{dt} - \frac{d(E_{HL})}{dt} \quad (1)$$

Conservation of mass:

$$\frac{dm_p}{dt} = \rho \cdot S \cdot r \quad (2)$$

Propellant burn rate, r is a function of the space-average pressure and fits the experimental data of most propellants in the form of following equation:

$$r = B P_c^n \quad (3)$$

where B and n are constants based on the experimental data.

Nobel-Abel equation of state defines the relationship between the chamber pressure, volume and the temperature as follows:

$$P_c[V_c + A_p x - \frac{C - m_p}{\rho} - \eta m_p] = m_p F \frac{T}{T_0} \quad (4)$$

The chamber pressure derived from the equation of state is used to determine the acceleration of stroking mass using Newton's second law.

$$m \frac{d^2 x}{dt^2} = P_c A_p - F_f - F_{ext} \quad (5)$$

In addition to the friction forces, the only external load the blade encounters is the resisting loads caused by the riser bundle during the cut. Ideally, this force is determined by test or estimated based on the material strength. However, the unusual configuration of the flight cable and the lack of flight configuration test hardware during the initial development phase and the fact that the resisting loads are dependent on the blade velocity required the use of a high fidelity explicit transient finite element model.

Hi-Temp was selected as the energetic material to be used on the cutter assembly design. Hi-Temp is an RDX based propellant with relatively good ignition sensitivity at ambient pressure and a burn rate of about 1.6 in/sec at 5,000 psi and has a well established usage base on similar guillotine applications. In general, the published ballistic properties of Hi-Temp match well with internal ballistic codes without significant tweaking. To verify and refine the ballistic parameters, a sample Hi-Temp loaded cartridge was tested in a 4.2 cu-in closed bomb and the CADPROG input parameters were baselined as shown in Fig.3. Only a minor adjustment was needed on published burn rate coefficients.

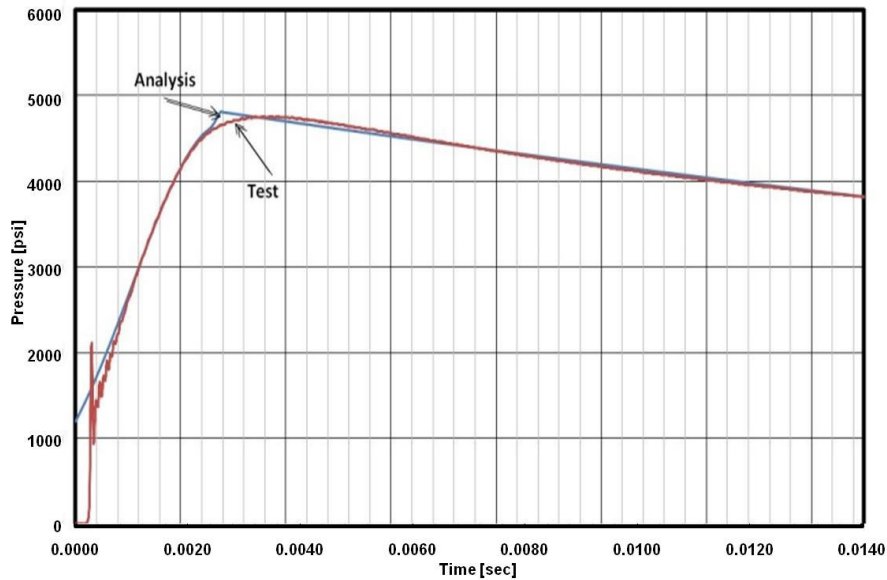


Figure 3. Closed Bomb Data and Analysis

III. Finite Elements Model

To evaluate the riser cable shear resistance loads and the blade performance, an LS-DYNA Finite Elements Analysis (FEA) model was created. LS-DYNA is an explicit FEA code that uses time integration to solve short duration transient and highly nonlinear dynamic problems. Figure 4 shows the finite elements model used for this study. The simplified FEA model consists of a blade, anvil, housing wall and the steel riser cable bundle. The flight

configuration riser cable has a unique four-strand cross-section and for simplicity was modeled as a steel rod. A plastic-kinematic material model with eroding contact elements was used. The steel blade and the anvil were also modeled with plastic-kinematic eroding elements.

The fast transient nature of the blade action and the fact that the blade is an internal part of the cutter assembly made it difficult to accurately measure the blade velocity. Although the break wires were placed on top of the cable bundle and the top surface of the anvil, the data obtained from these limited locations was not enough to establish an accurate velocity profile of the blade during its stroke. Nevertheless the break wires still provided valuable location data to refine the FEA model.

The penetration depth of the blade into the anvil was also used as another measuring stick for the blade velocity. LS-DYNA typically uses plastic failure strain criteria to simulate material failures such as cracking, shear and tensile failures. The failure strain of the cable bundle was refined by comparing the penetration depth calculated with LS-DYNA to the post test measurement of the anvil penetration depth.

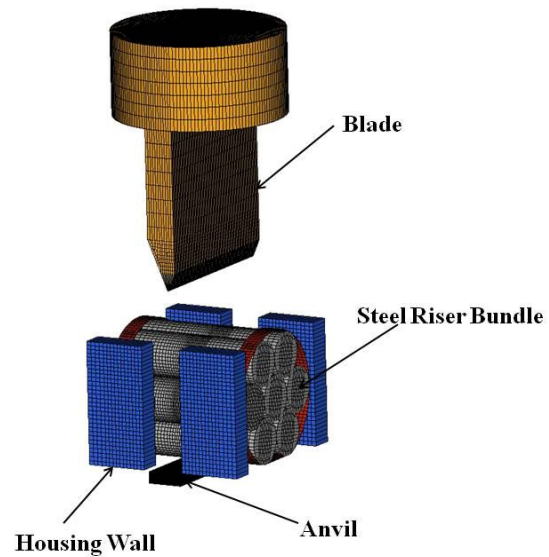


Figure 4. Riser Cutter LS-DYNA Model

IV. Combined Analytical Approach

As noted earlier, for additional margin, a bundle of seven substitute cables rather than six flight-like cables was used during the initial analysis and testing phase. CADPROG was used to obtain a preliminary pressure profile. The CADPROG input was adjusted for heat loss to match the preliminary test firings.

The next step was to set up the LS-DYNA simulation using the preliminary pressure profile to refine the cable bundle resistance during cable severance. The contact between the blade and the cable bundle was simulated using LS-DYNA keyword CONTACT_ERODING_SURFACE_TO_SURFACE to allow continuous contact during the cut. The blade penetrated approximately 0.30 inch into the steel anvil when tested with substitute cable bundle. LS-DYNA analysis with initial estimated cable material failure criteria showed only 0.24 inch penetration as shown in Fig. 5, which indicated that the cable failure strain used for LS-DYNA simulation needed to be slightly reduced to achieve a 0.30 inch penetration. Figure 6 shows the correlation between the CADPROG and LS-DYNA with and without the target material.

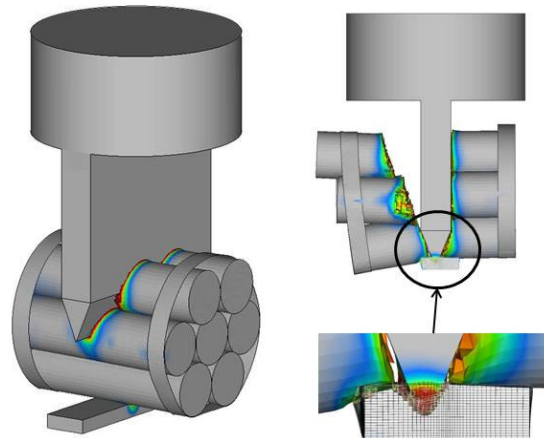


Figure 5. Finite Elements Simulation (plastic strain contours shown)

The sequence of the iterative analysis between the two codes was as shown in the Fig. 6 labels and summarized below:

- 1) The analysis sequence started with a simple ballistic analysis with no target.

- 2) The pressure profile from this analysis was fed back into the LS-DYNA simulation as a load input and the simulation was performed with no target cable.
- 3) The same simulation was then repeated by adding the target cable to the model. The previously established cable failure strain was used as the cable failure criteria. The cable resisting loads were calculated by using LS-DYNA keyword DATABASE_SPCFORC, which prints out the net reaction force at the nodal fixed boundary conditions at the bottom of the anvil. This feedback analysis between CADPROG and LS-DYNA was repeated for minimum and maximum charge loads and an average cable resisting force of 4,500 pounds was calculated.
- 4) Having established the external resisting load, Eq. (5) was solved again in CADPROG for more accurate and realistic pressure profile and propellant sizing exercise.

It should be noted that because these two codes are independently solved, the feedback between the two codes is not performed simultaneously in real-time. This can only be possible by inserting the internal ballistics solution into LS-DYNA as a subroutine for each time step. A true real-time interaction of these codes can provide a more accurate load-dependent pressure profile. For this study, the pressure and external load outputs of CADPROG and LS-DYNA were used as fixed input into the other code. A few iteration cycles were needed for an acceptable balance.

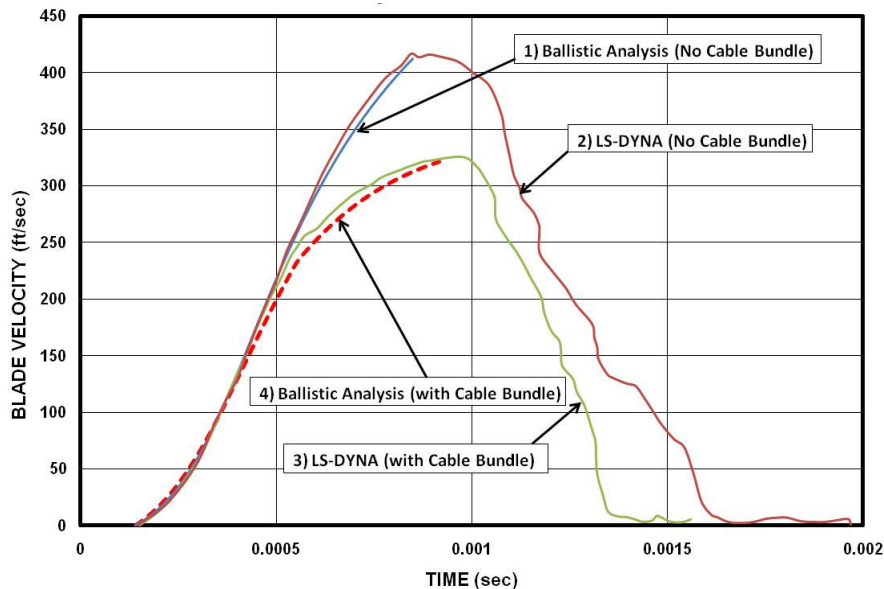


Figure 6. Blade Velocity - LS-DYNA vs CADPROG

V. Propellant Charge Sizing

NASA pyrotechnic specifications require that all cartridge actuated devices to be capable of performing its function with 85% of the minimum and 115% of the maximum charge weight. The charge sizing analysis using CADPROG was performed by baselining the 85% charge weight with a single cartridge first and working its way up toward the 115% charge weight with dual cartridges.

The primary design factors for the optimum charge weight that generates the lowest possible maximum pressure are the initial free volume, piston diameter, propellant burn rate and geometry, shear pin strength and the total stroke. The piston diameter was set to 1.5 inch and the maximum stroke to 1.75 inch due to space limitations. Ideally, maximizing the initial free volume (ullage) provides the most efficient pressure profile throughout the

power stroke. Within the design space and the structural limitation, the maximum possible volume was utilized. As a result, the shear pin strength and the propellant weight remained the two major variables to be predicted for the optimum design.

Figure 7 depicts the comparison of the ballistic analysis prediction to the test data for the single 85% cartridge. Using the LS-DYNA resisting load predictions and the heat loss estimates based on the initial firings with substitute cable bundle, an excellent match was achieved between CADPROG simulation and the test data. Note that the prediction curve was shifted manually to match the ignition delay.

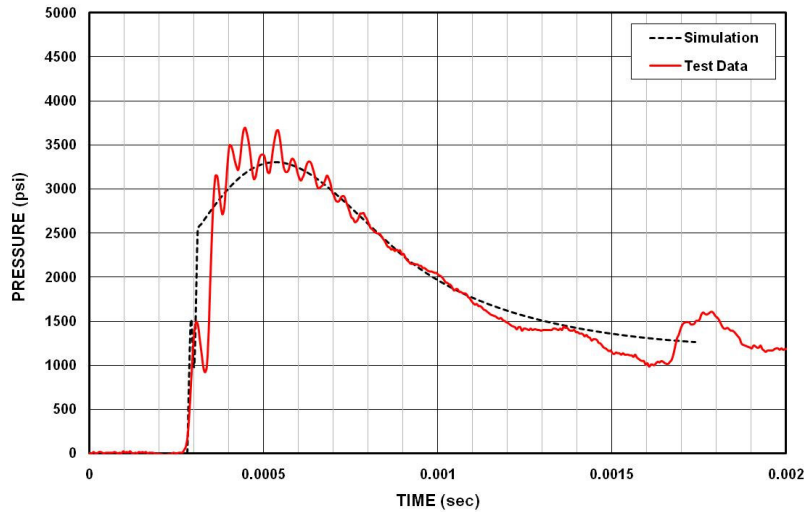


Figure 7. Single 85% Loaded Cartridge Pressure Data and CADPROG Prediction

For a relatively short stroking CAD with small initial free volume such as this cutter assembly, the performance difference between the 85% single cartridge and 115% dual cartridges can be huge. All structural margins of the cutter assembly should be based on the maximum pressure obtained from the dual 115% cartridges or 1.2 times the dual nominal cartridges, whichever is greater. CADPROG predictions for dual nominal and 115% cartridges were in excellent agreement with the results obtained from test firings as shown in Figure 8 and 9.

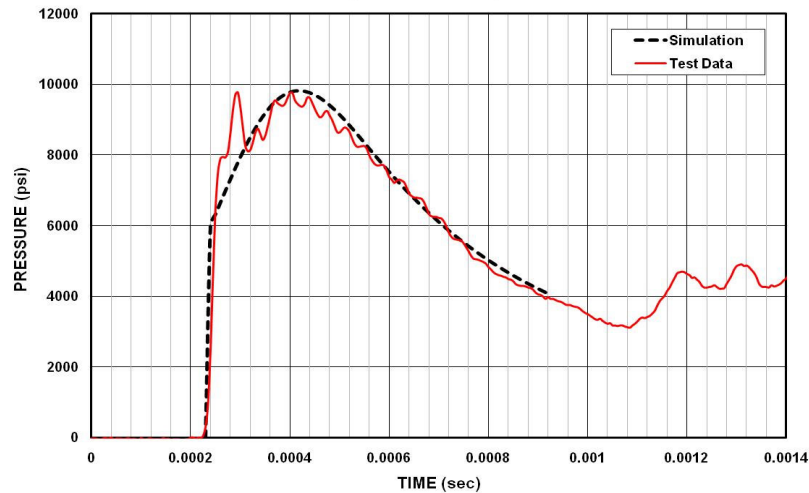


Figure 8. Dual Nominally Loaded Cartridges Pressure Data and CADPROG Prediction

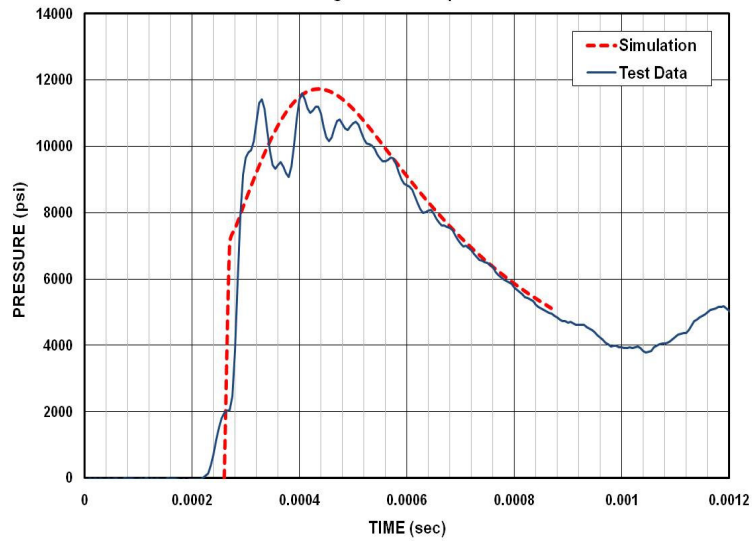


Figure 9. Dual 115% Loaded Cartridges Pressure Data and CADPROG Prediction

CADPROG and LS-DYNA analysis were not only used to establish the charge weight but also provided valuable input to the vehicle design engineers for structural analysis. In the absence of an accurate method of measuring the blade impact velocity, CADPROG combined with LS-DYNA external load input provided the velocities for three cases shown in Figure 10. These predictions were used to assist in the design and the dynamic analysis of the flowerpot and the vehicle interface.

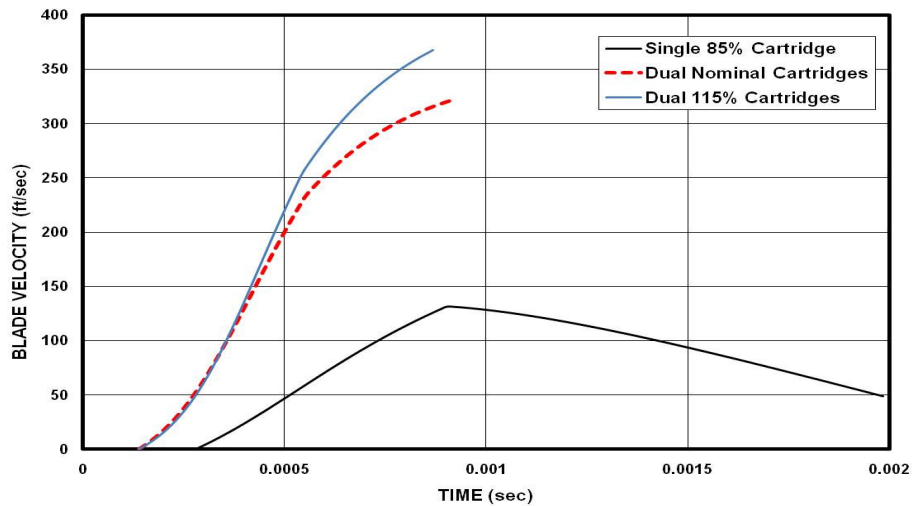


Figure 10. Blade Velocity Profile for Three Cases

VI. Conclusion

Final Design - The flowerpot design matured so a reusable cutter prototype and the PTV drop test cutter were designed using a workhorse cutter test data, analysis and simulation.

Procurement - Government procurements are controlled by the FAR and large contract values can create schedule and delivery delays. Therefore the cutter was designed to be reusable to support follow on tests. The prototype was fabricated in-house at the same time the drop test cutters were fabricated offsite. The prototype cutter was test fired 6 times using the substitute target before the actual target cable arrived and while the test cutters were in fabrication.

Final Testing - Test risers with six target cables were successfully cut. The post cut anvil penetration matched the substitute cable cuts and more blade wear occurred as expected. In short, the riser cutters performed as predicted and as designed. An excellent agreement between the firing test data and the analytical methods was established. Consequently, the development program was completed ahead of schedule.

From the computational point of view, it was shown that LS-DYNA and CADPROG can be utilized in tandem to provide initial estimates for ballistic and structural design. Although this approach provided acceptable results for the riser cutter design presented here, for more complicated CAD systems with variable external loads, a true real-time feedback method between LS-DYNA and CADPROG is essential. Future studies will focus on establishing an LS-DYNA user-defined equation-of-state that will solve the CADPROG equations within LS-DYNA.

Acknowledgments

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