Application of Internal Ballistic Modeling in the Design of a Bolt Cutter

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Abstract

Utilization of an internal ballistic modeling tool combined with strategic characterization testing was shown to significantly aid the development and qualification of a pyrotechnic cutter. A quasi-equilibrium model was used to simulate the interdependencies between the thermodynamic and mechanical variables of the pressure cartridge, the cutter and the target. The cutting force dynamics, or the interaction between the cutter's blade and the target material, was considered to have the greatest design impact. To reduce the risk, a quasi-static cutting force model of blade force vs. target penetration was generated by running simple tests. The full performance model including the quasi-static cutting force estimation was shown to provide a high degree of accuracy and predictability for the actual cutting event and proved to be beneficial in accelerating the concept to development and qualification cycle.

Nomenclature

P	=	pressure
v	=	specific volume
b	=	covolume
R	=	gas constant
x	=	mass fraction
λ	=	linear burn fraction
a	=	burn rate coefficient
n	=	burn rate exponent
r	=	linear distance to achieve complete burn
m	=	gas mass
w	=	initial charge weight
$f(\lambda)$	=	propellant form function, fraction of mass burnt as function of linear burn fraction
T, T_0	=	temperature and initial temperature
q_{burn}	=	heat released by propellant burning
q_{loss}	=	heat lost through heat transfer
W_b	=	boundary work
h, u	=	specific enthalpy and energy
h_c	=	convection coefficient
SA	=	surface area
Ma	=	orifice throat mach number
γ	=	specific heat ratio
c_dA	=	orifice throat area with discharge coefficient
P_b	=	pressure acting on blade

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Introduction

Internal ballistic modeling of pyrotechnic devices early in the development phase is an important tool to help understand design sensitivities and aid in the selection of critical design parameters. When the device requires predictable fracture or permanent deformation of structural elements, the dynamics and non-linear responses of the structural elements play a significant role in the overall performance of the pyrotechnic device. Examples of such devices are pyrotechnic cutters and pyrotechnic valves. For the pyrotechnic cutter, the material responses of the blade and the target, and for the pyrovalve, the fracturing of the material to open up the flow passage, have significant impact on the overall design of the device. These material responses are highly non-linear and transient so detailed strength and fracture models for such events are often not available. However, simplified models grounded in strategically designed engineering tests can often be a valuable substitute when timelines do not support obtaining specific high fidelity material models. Furthermore, there are many design factors that influence variability and cutting performance, including blade and anvil material, hardness, and geometry which can be captured in such tests. It was suggested by H. Lee [1] that a quasi-static (QS) cutting test could be a potentially useful means to characterize the complex cutting action. It is the goal of this work to demonstrate the applicability of this idea.

Chemring Energetic Devices (CED) has recently designed and qualified the pyrotechnic bolt cutter depicted in Figure 1 to reliably sever a 6.35 mm (0.250 inch) diameter custom 455 H1000 steel target rod. Internal ballistic modeling of the device was performed and supplemented with a simple, attainable fracture model tailored to the specific target being severed. The simple fracture model testing was performed early in the development phase knowing it would have major implications in the cutter design. The ballistic model and the fracture model were then used to help select critical design features such as the shear pin size and required propellant charge.

Figure 1. Qualified Pyrotechnic Bolt Cutter

Cutter Description and Analytical Model

The pyrotechnic bolt cutter is a guillotine style cutter designed to sever a 6.35-mm (0.250-inch) diameter custom 455 H1000 steel rod. The cutter includes an inert cutter body with a hardened blade secured within the body using a shear pin and an anvil which reacts to the target during cutting forces and prevents the blade from exiting the cutter body following completion of target severance. The cutter body is powered by a hermetically sealed pressure cartridge containing a main charge (RDX-based composite propellant) and is initiated using redundant initiators each primarily containing a $BKNO_3$ ignition charge. A conceptual layout is provided in Figure 2.

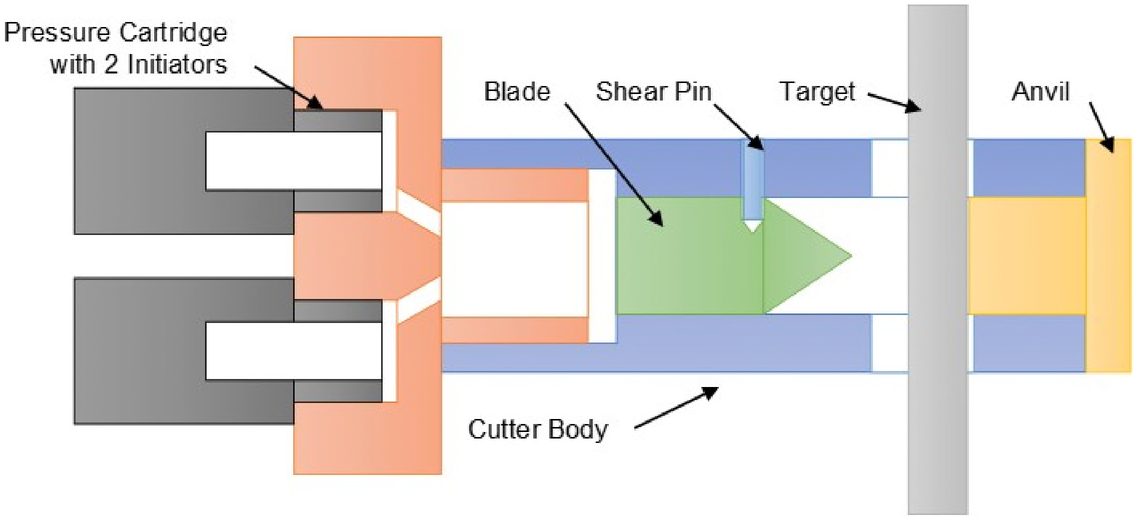

Figure 2. Conceptual Layout of Pyrotechnic Bolt Cutter

Upon receiving the all-fire stimulus, the $BKNO_3$ ignition charge within each initiator produces high temperature products of combustion which flow through small passages connecting the pressure cartridge initiator ports to the main charge chamber. These products ignite the main charge, which produces high pressure and high temperature gases behind the cutter blade. When the cutter body pressure reaches a sufficient pressure, the shear pin restraining the cutting blade fractures and the blade begins traveling toward the target. As the blade penetrates the target, resistive cutting forces oppose blade motion until uncontrolled crack propagation occurs and fractures the remaining target section, at which point there is little resistance to motion and the blade completes the stroke, striking the anvil.

The internal volume inside the cutter body and pressure cartridge initiator ports, the main charge, shear pin fracture force, and free stroke between blade tip and target are critical design parameters. These values require careful selection to ensure successful severance of the target. An analytical model was created to study these parameters and drive the design and charge selection.

Analytical Model

CED's internal ballistic model (called CIBAC, CED Internal Ballistics Analysis Code) captures the pertinent physics occurring within the cutter including propellant burning (solid to gas conversion), thermodynamics, the mechanics of the cutting blade's motion, high speed gas flow between internal chambers, heat losses, and resisting forces associated with target severance. At its core, CIBAC is a lumped parameter model in which all solid propellant is converted to an inert working fluid that flows between control volumes and performs boundary work through volume expansion. CIBAC is described by the following equations where index i specifies the gas species (igniter product, output charge product, or initially present gas) and index j specifies the control volume (CV, three total in the device presented herein), and index k specifies the orifice (2 total in the device presented herein).

$$P_j\left(v_j - \bar{b}_j\right) = \bar{R}_j T_j \tag{1}$$

$$\bar{R}_j = \sum_i x_{i,j} R_i \tag{2}$$

$$\bar{b}_j = \sum_i x_{i,j} b_i \tag{3}$$

$$\dot{\lambda}_{i,j} = \frac{a_i P_j^{n_i}}{r_i} \tag{4}$$

$$\dot{m}_{burn_{i,j}} = w_{i,j} f_i'(\lambda_{i,j}) \dot{\lambda}_{i,j} \tag{5}$$

$$\dot{m}_{i,j} = \dot{m}_{in_{i,j}} - \dot{m}_{out_{i,j}} + \dot{m}_{burn_{i,j}} \tag{6}$$

$$\dot{T}_j = \sum_i \left[\dot{m}_{burn_{i,j}} q_{burn_{i,j}}\right] - q_{loss_j} - \dot{W}_{b_j} + \sum_i \left[\dot{m}_{in_{i,j}} \left(\hat{h}_{in_{i,j}} - u_{i,j}\right)\right] - \sum_i \left[\dot{m}_{out_{i,j}} \left(\hat{h}_{i,j} - u_{i,j}\right)\right] \tag{7}$$

$$q_{loss_j} = h_{c_j} SA_j \left(T_j - T_{w_j}\right) \tag{8}$$

$$\frac{T_{w_j} - T_{0_j}}{T_j - T_{0_j}} = erfc(0) - e^{\frac{h_{c_j} \alpha_j t}{k_j^{\,2}}} erfc\left(\frac{h_{c_j}\sqrt{\alpha_j t}}{k_j}\right) \tag{9}$$

$$Ma_p = \min\left\{\left(\left(\left(\left(\frac{2}{\gamma_p+1}\right)^{-\frac{\gamma_p}{\gamma_p-1}}\right)^{\frac{\gamma_p-1}{\gamma_p}} - 1\right)\left(\frac{\gamma_p-1}{2}\right)^{-1}\right)^{\frac{1}{2}}, 1\right\} \tag{10}$$

$$\dot{m}_p = c_{d_p} A_p Ma_p \sqrt{\gamma_p R_p \frac{T_p}{1+\frac{\gamma_p-1}{2} Ma_p^2}} \left(\frac{1}{1+\frac{\gamma_p-1}{2} Ma_p^2}\right)^{\frac{1}{\gamma_p-1}} \tag{11}$$

$$P_b A_b - F_c = m_b \ddot{X}_b \tag{12}$$

Equations (1) – (3) describe the equation of state for the products of combustion assuming Amagat's Law of Partial Volumes for the gas mixture. Equations (4) and (5) describe the rate of solid propellant to gas conversion (burning). Equation (6) expresses continuity for the gaseous products and Equation (7) expresses conservation of energy for each CV. Equation (8) and (9) describes convective heat losses within the device assuming an infinite plane wall and Equations (10) – (11) describe isentropic nozzle flow through the orifices connecting CVs. Equation (12) expresses conservation of momentum for the cutter blade. The cutting force, Fc which appears in the momentum equation is the major unknown which this work addresses through the use of a simplified quasi-static cutting force profile. This model was implemented in MATLAB and used to evaluate the cutter and to drive critical design decisions.

Cutter Force Characterization

The main energy and power requirement for the cutter is driven by the resistive cutting force; therefore, a reasonable analytical model is necessary to build a useful performance model. The high speed cutting event is complex and the cutting force depends not only on the target's quasi-static (QS) stress versus strain characteristics (of which the data are typically available in public domain), but also on the materials strain rate hardening and thermal softening behavior as well. Additionally, the fracture criteria of the target is complex and the detailed failure criteria for the target (Johnson-Cook failure or similar) is not readily available. Such lack of detailed material characteristics including the fracture criteria is not uncommon in typical design and development of these devices. In reality, schedule demands often preclude the raw material characterization required to obtain high fidelity strain rate and temperature dependent material models. In lieu of a detailed cutting force model, a simple model based on the quasi-static cutting force versus cutting distance was selected as alternate approach. The model is conceptually illustrated in Figure 3 and assumes an increasing force resists increasing blade penetration until a critical cutting depth is achieved leading to uncontrolled crack propagation through the remaining cross section at which point the target is fully severed. Such a model is admittedly less accurate than an explicit material model or fracture model, but is quick and easy to determine.

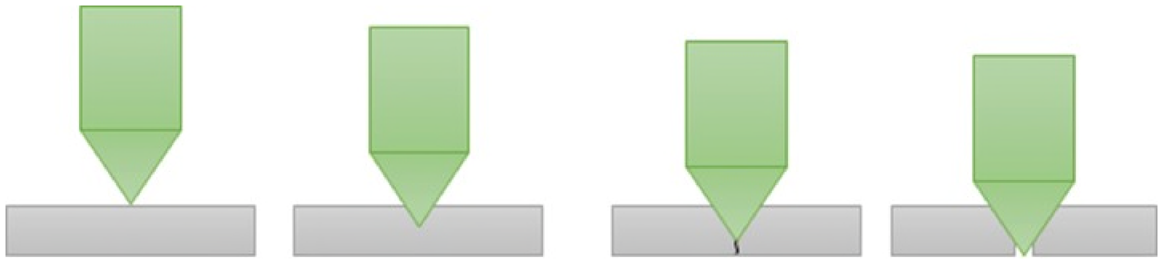

Figure 3. Illustration of Cutting Depth Leading to Uncontrolled Crack Propogation

The quasi-static model was determined by severing three (3) 6.35-mm (0.250-inch) custom 455 H1000 sample targets using a representative cutter. The blade was forced against the target using a hand pumped hydraulic ram while hydraulic pressure was monitored and ram stroke measured using an linear variable differential transducer. The collected data provided a cutting force vs distance curve which was enveloped using a piecewise linear lookup table for use in the internal ballistic model. A photo of the test setup and the resulting cutting force vs distance model is provided in Figure 4. In each of the three (3) samples, the blade penetrated the target between 3.56 mm (0.14 inch) and 3.81 mm (0.15 inch) before fracture occurred with uncontrolled crack propagation through the remaining section of the target. Within the context of the simple quasi-static cutting force model, this was used as the critical cutting distance to achieve fracture and the cutting force was reduced to zero once this was reached.

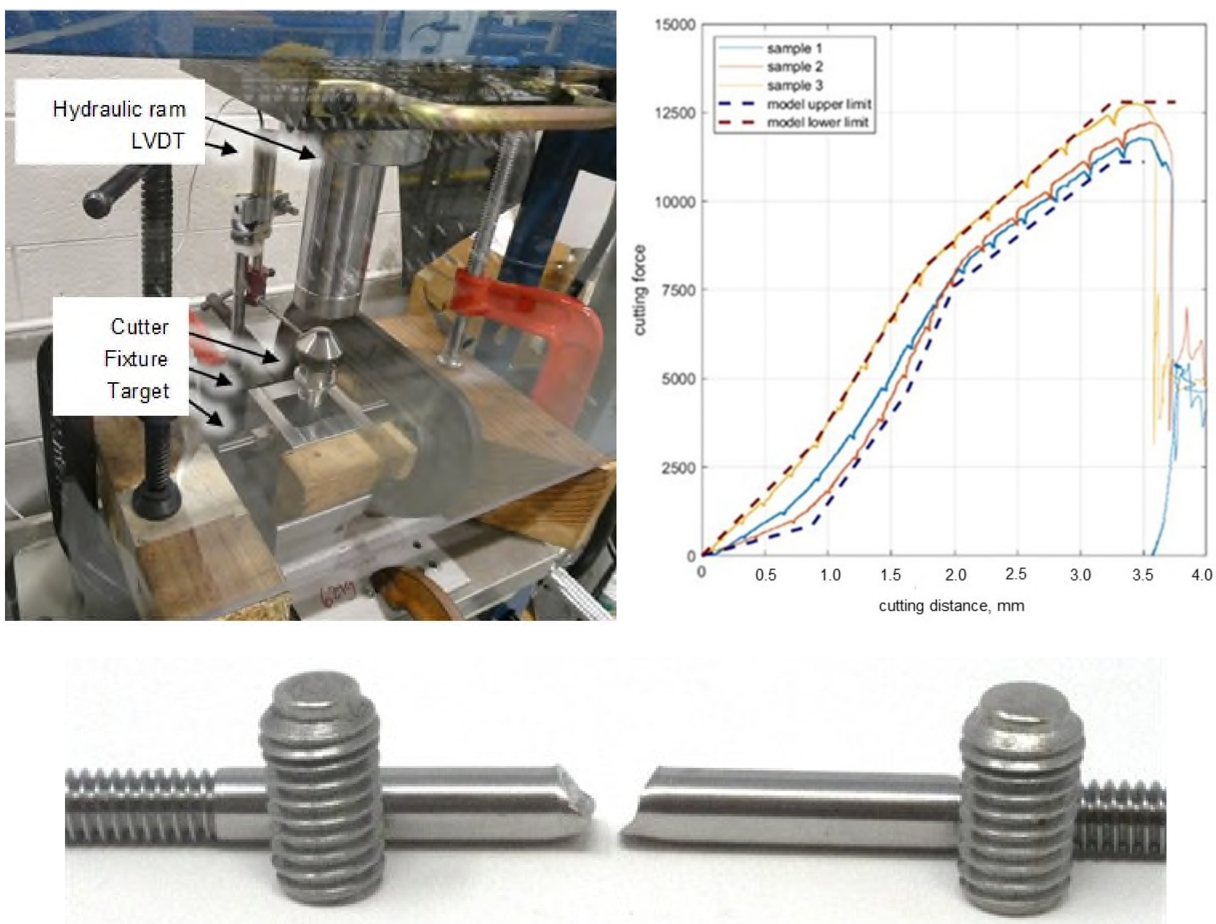

Figure 4. Cutting Force Measurement Setup (left); QS Cutting Force Model (right); Severed Target (bottom)

Model Validation

The analytical model parameters were continuously modified and validated as data was collected during the development phase of the program. Closed bomb (2 cm^3) testing, depicted in Figure 5, was performed to characterize the pressure cartridge output in a small volume and to ensure the main propellant modeling characteristics (burning form function, linear burning rates, impetus, etc.) were representative of the propellant lot being used. The analytical model previously described is readily tailorable to a closed bomb configuration by turning off mass flow through all orifices and fixing the blade such that no boundary work is performed by the gas products. Results of a typical closed bomb trace and model prediction is presented in Figure 6 and demonstrate a satisfactory match, indicating the model accurately captures the burning and gas generation characteristics of the pressure cartridge.

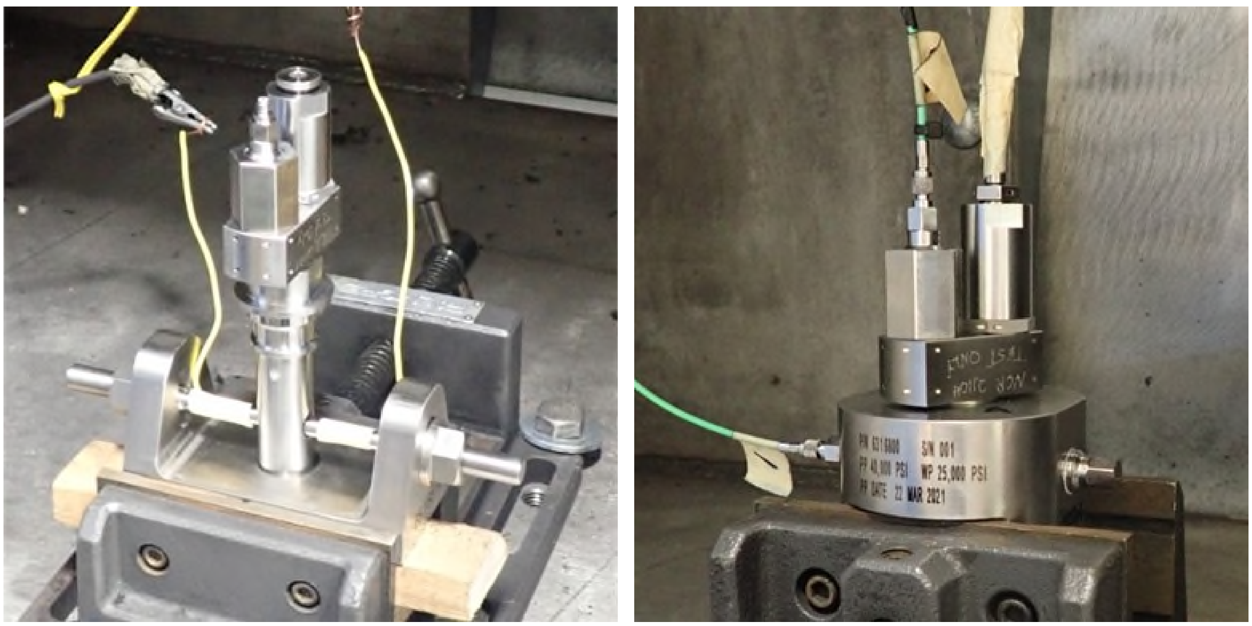

Figure 5. Functional Test Setup (left) and 2-cm^3 Closed Bomb (right)

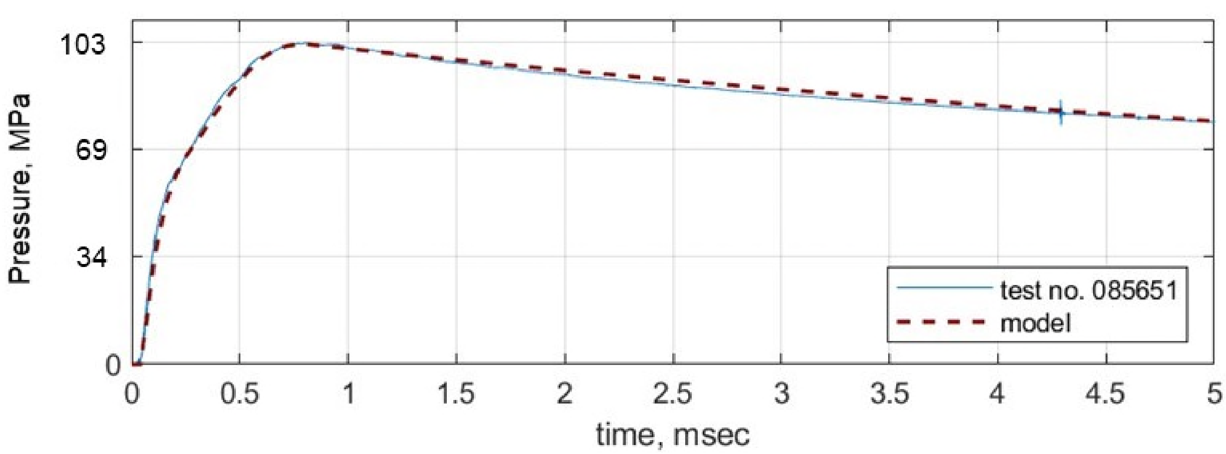

Figure 6. 2-cm^3 Closed Bomb Model Comparison

The analytic model of the cutter was evaluated on an on-going basis as part of CEDs charge development program and was used to drive subsequent charge development loadings. The purpose of the charge development program was to determine the critical charge above which the cutter would successfully sever the target and below which the target would not be fully cut. An initial charge was selected using the analytic model setup based on the developed quasi-static severence mode, 2-cm^3 closed bomb test results, and initial engineering estimates for other model parameters. Initial baseline functional tests were performed (see Figure 5 for test configuration) and the model was refined based on the results then used to generate additional trial charges. The charge development effort is summarized in Table 1 with the loaded charge expressed as a fraction of the final determined production charge. Note that no peak pressure is reported for tests performed with 2 initaitors as pressure was measured in the redundant initiator port and a second initaitor precluded measurement.

Table 1. Charge Development Test Results

Unique Test No.	No. Initiators	Loaded Charge/ Final Charge	Test Temp	Peak Pressure	Target Severence
085653	1	109%	Amb	79 MPa	Pass
085654	2	110%	Amb	-	Pass
085883	1	101%	Amb	*Not Captured*	Pass
085884	1	94%	Amb	78 MPa	Pass
085885	1	86%	Amb	73 MPa	Pass
085886	1	77%	Amb	71 MPa	Pass
085887	1	69%	Amb	63 MPa	Pass
085945	1	61%	Amb	65 MPa	**Fail**
085946	1	53%	Amb	61 MPa	**Fail**
085949	2	152%	Amb	-	Pass
085950	2	160%	Amb	-	Pass
085951	2	120%	Hot	-	Pass
085952	2	136%	Hot	-	Pass
085953	1	80%	Cold	65 MPa	Pass
085954	1	70%	Cold	64 MPa	Pass

The analytic model output for test numbers 085887 and 085945 are presented in Figure 7 along with the measured test pressure. These two test conditions represent critical cases as the charge used in test number 085887 succesfully severed the target and a small reduction in charge, test number 085945, failed to fully cut the target. These cases therefore represent a critical test of the analytic model's usefulness, namely the ability to accurately predict the critical charge.

The analytic model correctly captures full severence of the target in simulation of test number 085887 and failure to fully cut in test number 085945. Post-function measurements of blade penetration without severence from test number 085945 indicated the blade had penetrated the target 3.45 mm (0.136 inch) prior to the blade momentum being halted without target severence and agree well with analytic model predictions. Overall peak pressures and secondary peak pressures (occurring after blade reaches end of stroke) from the model agreed well with measurements (within 5%) although the model predicts a slightly longer action time (approximately 0.2 ms). Examination of the pressure curve indicates the initial pressure rise may be predicted too long and could be a result of flake breakup resulting in a different form function than that which was implemented based on 2-cm^3 closed bomb testing. Despite this timing difference, the model was determined to be sufficient for engineering application based on the overall agreement in peak pressures, successful prediction of total blade penetration, and overall time scale accuracy being well within the device's required function time.

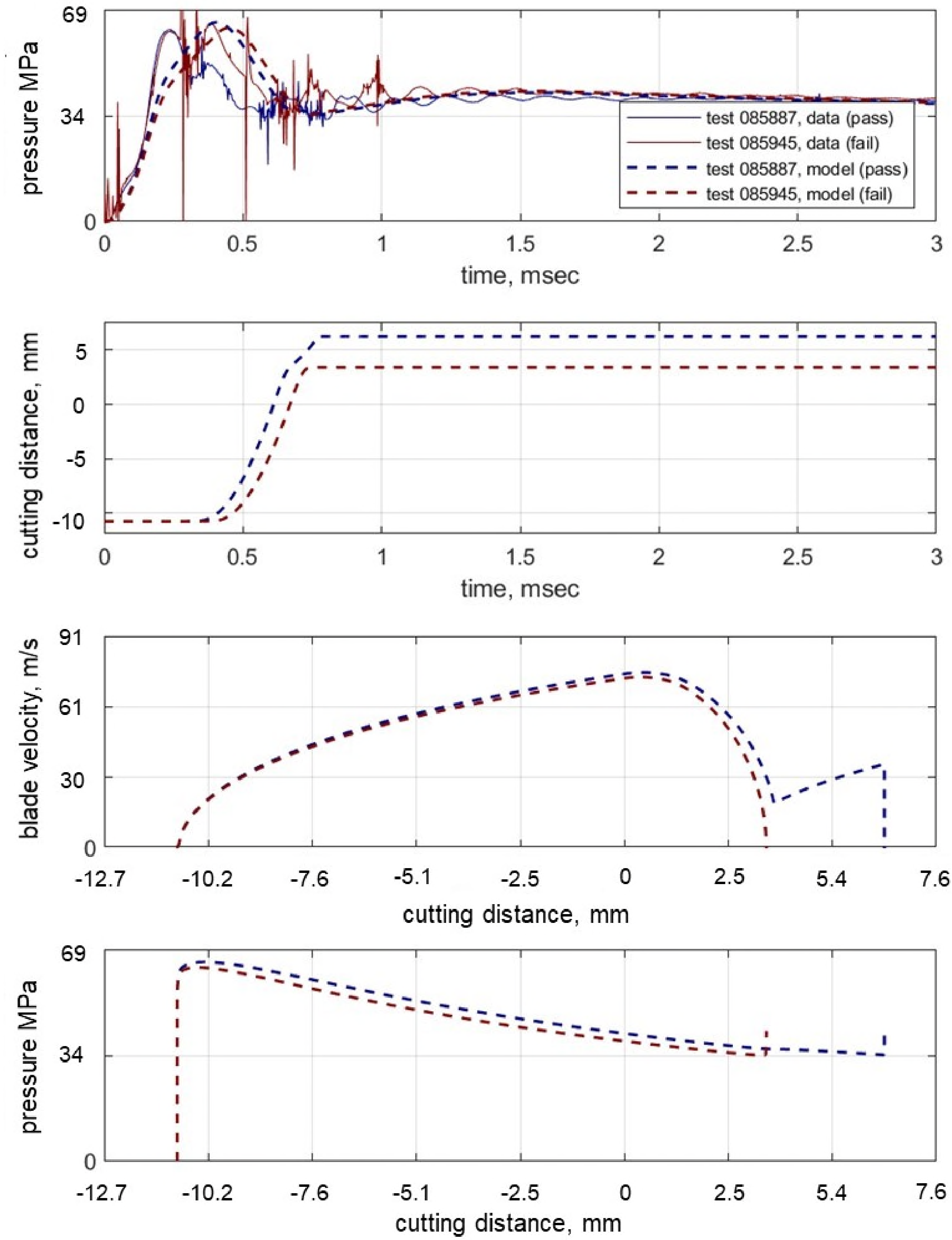

Figure 7. Cutter Model Comparison with Measured Pressure Data (top) and Additional Model Output

Cutter Distance Observations

The effect of increasing charge on the cutting depth prior to uncontrolled fracture is depicted in Figure 8 and is plotted as a function of the charge to nominal charge ratio in Figure 9. The depth of cut prior to uncontrolled fracture was estimated using a microscope and imaging software. Quasi-static samples exhibited a smooth cut and clean transition from blade penetration to uncontrolled crack propagation with approximately 3.68 mm (0.145 inch) of the severance occurring as a result of blade penetration. Charge ratios from zero (quasi-static data) up to approximately 110% of nominal resulted in very similar blade penetration depth prior to uncontrolled fracture and maintain the clean transition between penetration and crack propagation. At higher charge ratios (>140% of nominal charge weight) which resulted in higher pressures and cutting speeds, a dramatic reduction in blade penetration depth occurred and the clean transition from blade penetration to crack propagation was lost. Based on these results, it is believed that the quasi-static cutting model with a failure criteria based solely on blade penetration was a reasonable model choice for the cutting speeds encountered during a typical cutter firing, but would have been a poor choice for higher charge (cutting speed) conditions.

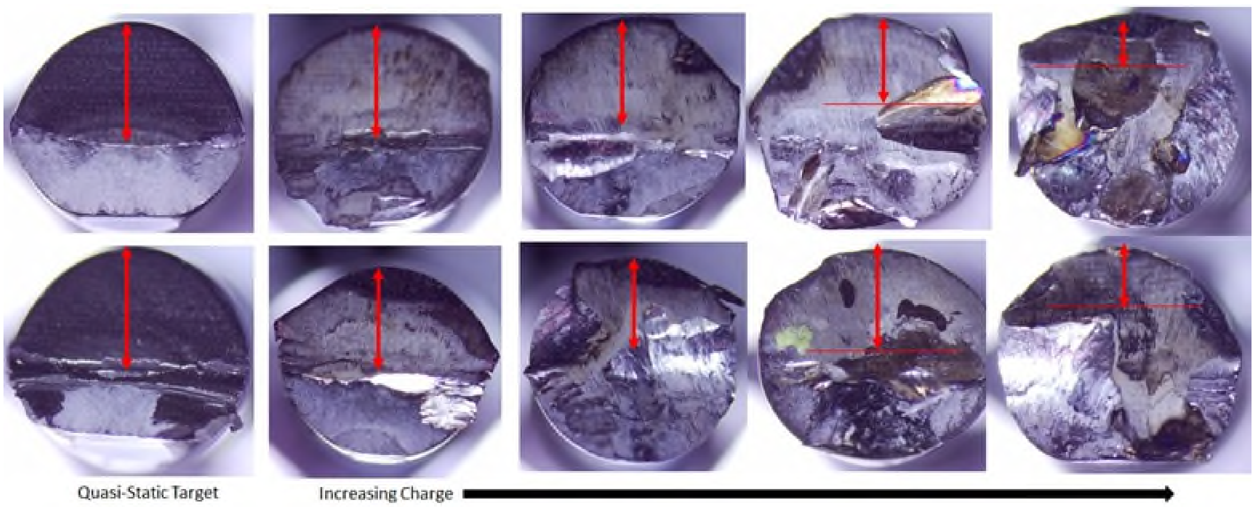

Figure 8. Effect of Cartridge Charge on Cutting Depth/ Surface

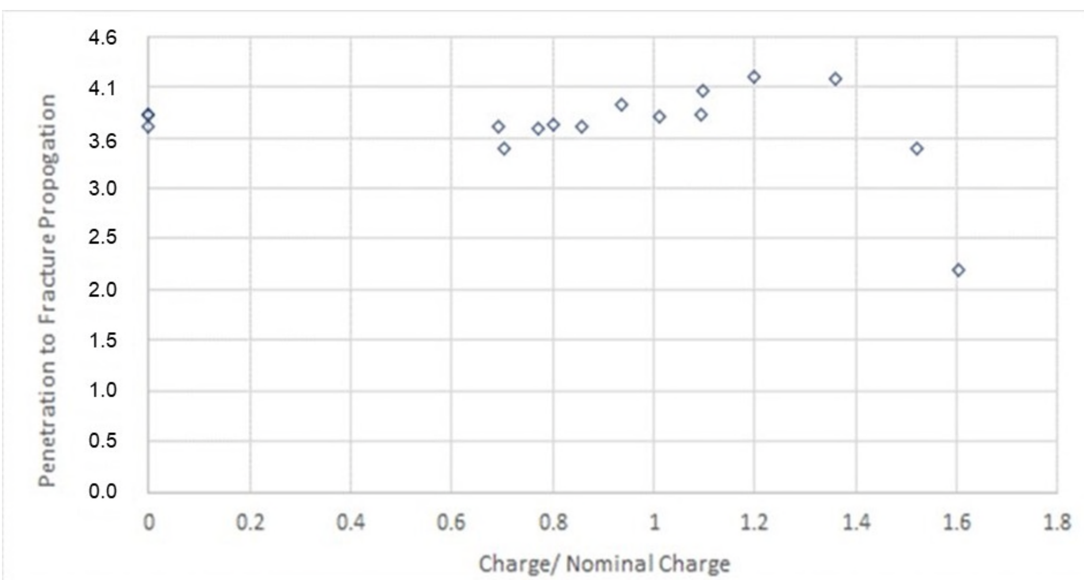

Figure 9. Cutting Depth to Achieve Uncontrolled Fracture Propagation as Function of Charge Ratio

Suggested Extension of Work

The presented model can be readily extended to cutters of differing size or target materials where the accuracy is tied to the fidelity of the cutting force estimation. When developing pyrotechnic cutters such as that presented in this paper, it is recommended that the quasi-static cutting force test be performed on the target samples. If target samples or representative cutter blades for testing are not available, then it may be reasonable to scale the results based on size and strength of target relative to available QS data. CED has not yet evaluated the accuracy of scaling results, although future work could include an assessment of scalability to determine if a linear scaling is appropriate or a more complex scaling scheme is required.

While the subject of this work was a pyrotechnic cutter, there are many other pyrotechnic devices that require the fracturing of structural members. Modeling of these devices can be improved by performing similar force versus stroke characterization testing. The physics of pyrotechnic or ballistic events are such that that the propellant burning, the thermodynamics, and the mechanical responses are highly interdependent. Therefore, having a good starting point model of the resisting force profile is critical to build a useful model that captures the structural elastic/plastic response and the failure criteria. As with the discussed cutting depth as a function of charge (or the cutting velocity), an assessment of the QS applicability would be needed on a case by case basis to verify that a reasonable model is obtained.

Conclusion

Internal ballistic modeling of pyrotechnic devices used to reliably fracture or sever structural members can be supplemented with simple-to-obtain quasi-static force versus stroke characterization. It was shown to significantly help with the selection of design parameters and then predict performance under different design cases. An example of how this can be accomplished was provided for a recently qualified bolt cutter but this work can be extended to other devices with similar requirements. It is important to compare the quasi-static results with high speed functional results to determine if the fracture event occurs on a time scale at which the quasi-static force versus stroke curve gives a reasonable approximation or if more complex material strength and fracture models are warranted, such as during a detonation driven event. Future work may include development of a method to scale 6.35-mm (0.250-inch) diameter target bolts to different sized targets or different materials.

References

1. Lee, H., "Underwater Performance Characterization of A ballistic Guillotine Cutter at Operating Temperature Extremes" *50th AIAA/ ASME/ SAE/ ASEE Joint Propulsion Conference*, July 2014