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*Modeling Experiments
That Simulate Fragment Attacks on
Cased Munitions*

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*Modeling Experiments
That Simulate Fragment Attacks on
Cased Munitions*

Jerry F. Kerrisk

MODELING EXPERIMENTS THAT SIMULATE FRAGMENT ATTACKS ON CASED MUNITIONS

by

Jerry F. Kerrisk

ABSTRACT

Roberts and Field (1993) have conducted experiments to observe the behavior of a cased high explosive (HE) charge subject to fragment attack at impact velocities below those needed for shock initiation. Two- and three-dimensional hydrodynamic calculations have been done to model these experiments. Questions about the degree of confinement of the HE and about the condition of the HE during the impact were addressed. The calculations indicate that the HE was not strongly confined in this experiment, primarily due to the lateral expansion of polycarbonate blocks on the sides of the target during the impact. HE was not ejected from the hole in the casing made by the projectile up to 30 μ s after the impact. There are hints from these calculations of how initiation of a homogeneous sample of HE might occur in the experiment. The first involves the reshock of a small amount of HE at ~ 20 μ s as a result of the impact of the sabot on the target. The second involves the heating of the HE from plastic work during the impact. The maximum temperature rise of the HE (exclusive of the small region that was reshocked) was ~ 80 k. However, this is the average temperature of a region the size of a computational cell, and phenomena such as shear bands or cracks could result in higher temperatures on a smaller scale than the cell size. The third involves heating of the HE from contact with the casing material. The maximum temperature rise of the casing material from plastic work is ~ 870 k. This temperature occurs at the edge of a plug of casing material sheared off by the projectile. Other parts of the casing are shock heated to higher energies but may not contact the HE.

INTRODUCTION

A series of experiments was conducted by Roberts and Field (1993) to observe the behavior of a cased high explosive (HE) charge subject to fragment attack at impact velocities below those needed for shock initiation. Figure 1 shows a sketch of the experimental arrangement. The steel projectiles were 0.55-cm diameter by 1.6-cm long and were partially contained in a nylon sabot. The front of the sabot was 0.8 cm behind the front of the projectile. The targets

were 1.9-cm diameter by 0.6-cm thick disks of HE, encased in 0.15-cm thick metal casing, and sandwiched between two 1.0-cm thick polycarbonate blocks. The behavior of the projectile, casing, and HE were photographed through the polycarbonate blocks with a framing camera. Different casing material, HE, and projectile front-end shapes were tested.

Fig. 1. Sketch of the experimental setup of Roberts and Field (1993).

Several of the questions raised by these experiments were difficult to address experimentally. These included questions about the degree of confinement of the HE during the impact and the details of the hydrodynamic conditions that led to initiation of the HE. Circumferential confinement of the HE was provided by the casing, but lateral confinement was provided by the polycarbonate blocks. To assess the degree of confinement of the HE, a three-dimensional hydrodynamic calculation of the impact was done. Results from this calculation also provided some information about the condition of the HE during the impact. This paper describes the results of the three-dimensional calculation and some additional two-dimensional calculations of the impact process.

DESCRIPTION OF THE CALCULATIONS

Figure 2 shows a sketch of the calculational setup for the three-dimensional calculation. The sizes of the HE, casing, and projectile were modeled as used in the experiment. The rear end of the sabot (beyond the back of the projectile) was not included. The lengths of the polycarbonate blocks in the x and z directions were also reduced. Because of the symmetry, only one-quarter of the problem was modeled. The PAGOSA hydrocode was used for the three-dimensional calculation (Kothe et al. 1993).

Two-dimensional calculations, viewing the experiment in the x-z and y-z planes, were also done. These calculations provided preliminary information about the timing of the impact and resulting damage. The MESA-2D hydrocode was used for the two-dimensional calculations (Cagliostro et al. 1990). A comparison of the results from the two-dimensional and three-dimensional calculations provides some insight into the need for the three-dimensional model.

Only one of the large number of experiments of Roberts and Field (1993) was modeled. A flat-end projectile with an impact velocity of $0.05 \text{ cm}/\mu\text{s}$ (500 m/s) was used. The HE was assumed to be Composition B (60% RDX and 40% TNT) without voids. The HE was not modeled as a reactive material.

Fig. 2. Sketch of the experimental setup as modeled with PAGOSA and MESA-2D.

Material Models

Linear U_s - U_p equations of state were used for all the materials. The Johnson-Cook strength model was used for the projectile, casing, and Composition B. This model represents flow stress (Y) as

$$Y = [A + B \epsilon^n] [1 + C \ln(\epsilon^*)] [1 - T^{*m}], \quad (1)$$

where ϵ = equivalent plastic strain, $\epsilon^* = \epsilon'/\epsilon'_0$, ϵ' = strain rate, $\epsilon'_0 = 1.0/s$, $T^* = (T - T_0)/(T_{\text{melt}} - T_0)$, T = temperature (or specific internal energy), T_0 = reference temperature (or energy), T_{melt} = melting temperature (or energy), and A , B , n , C and m are constants. The nylon sabot was modeled without strength, and an elastic-perfectly plastic strength model was used for the polycarbonate blocks ($Y = 0.0007$ Mbar).

Samples of the "silver steel" projectile material were obtained from Roberts and Field (1993), and mechanical property tests were done (Gray 1994). The results were fit to the Johnson-Cook model. Model parameters for the casing were taken as those for 1006 steel (Johnson and Holmquist 1989). Model parameters for Composition B were estimated from the data of Pinto and Wiegand (1993). Table I shows the Johnson-Cook parameters used for these materials.

Table I. Johnson-Cook Parameters

	Projectile	Casing	Comp. B
A (Mbar)	0.00613	0.00350	0.00054
B (Mbar)	0.014	0.00275	0
n	0.6	0.36	-
C	0.03	0.022	0.10
T_{melt} (Mbar cc/g)	0.00405	0.00405	0.00094
m	1.075	1.0	1.0

^a $T_0 = 0$.

Other Specifications

Variable cell sizes were used in these calculations. The minimum cell size (in the region where the projectile impacts the casing and HE) was 0.0125 cm. This size gives 22 cells across the radius of the projectile and 12 cells across the thickness of the casing. The largest cell size (at the periphery of the mesh) was 0.025 cm.

Calculations were run to 30 μs , where $t = 0$ is when the projectile first impacts the casing.

THREE-DIMENSIONAL CALCULATION

Figures 3, 4, and 5 show interface plots at 0, 5, 10, 15, 20, and 25 μs . In each figure, plots on the top are a view of the y-z plane and plots on the bottom are a view of the x-z plane. By 10 μs (Fig. 4 left), the projectile has moved ~ 0.3 cm into the target, and a noticeable lateral expansion of the polycarbonate-HE interface has occurred just behind the casing. By 15 μs (Fig. 4 right), the front of the sabot has reached the face of the polycarbonate blocks. The lateral expansion of the polycarbonate-HE interface continues. By 20 μs (Fig. 5 left), the sabot has reached the front of the casing in the x-z plane and has begun to extrude between the polycarbonate and projectile in the y-z plane. By 25 μs (Fig. 5 right), the plug of casing on the front of the projectile has separated from the remainder of the casing; the sabot continues to extrude into the region between the polycarbonate and the projectile. The polycarbonate-HE interface has moved up to 0.2 cm laterally. By 25 μs , the axial (z direction) velocity of the projectile has slowed from 0.05 cm/ μs (initial velocity) to 0.033 cm/ μs .

Figure 6 shows a plot of the total energy, kinetic energy, and internal energy of all the components in the calculation (1 Mbar cc = 10^5 J). Almost half the initial kinetic energy (in the projectile and sabot) has been converted into internal energy. There is a small loss of total energy, primarily from material moving off the mesh. Figure 7 shows the distribution of kinetic energy (top) and internal energy (bottom) among the various materials in the calculation. Most of the kinetic energy that has been lost (converted into internal energy) comes from the projectile. After the first few microseconds, essentially all the increase in internal energy of the components comes from plastic work.

Figure 8 shows a plot of the maximum specific internal energy (e_{max}) and maximum pressure (P_{max}) of the HE as a function of time. Up to ~ 20 μs , e_{max} is less than $\sim 1.0 \times 10^{-3}$ Mbar cc/g. Assuming a heat capacity of the HE of 1.2×10^{-5} Mbar cc/g k (1.2 J/g k), the maximum temperature rise of the HE is ~ 80 k. After the initial shock from the projectile impact (0 - 4 μs), P_{max} is less than ~ 5 kbar until ~ 13 μs . From 13 to 20 μs , P_{max} ranges from 5 to ~ 10 kbar; this may be caused by shocks from the impact of the sabot on the face of the polycarbonate blocks. Just after 20 μs , a very small region of the HE (a few cells) is reshocked. The maximum internal energy and pressure from ~ 20 to 23 μs occur in this region (see Fig. 8). The region is located near the HE-polycarbonate interface at $z = \sim 0.32$ cm (see Fig. 5 top left). This process occurs as the sabot and polycarbonate are driven into the HE. It represents a possible site for the initiation of the HE in this experiment.

Various parts of the casing are shocked and heated by impacts during the calculation. The shock from the initial impact results in a peak pressure of ~ 100 kbar on axis at the projectile-casing interface. Higher pressures (by about a factor of 2) might occur at the interface as a result of the curvature of the casing (Walsh et al., 1953). At ~ 18 μs the sabot hits the casing and from 18 to 22 μs , parts of the casing are reshocked. Most of this shock heating of the casing (initial and reshock) occurs at the outer surface, away from the HE. It is

TIME 5.0081

/TABLE/PR7/R4A/BRITISH HE INIT/COMP B/STEEL/0.05CM/MS/0.0125CM CELLS

TIME 5.0081

/TABLE/PR7/R4A/BRITISH HE INIT/COMP B/STEEL/0.05CM/MS/0.0125CM CELLS

TIME .0000

/TABLE/PR7/R4A/BRITISH HE INIT/COMP B/STEEL/0.05CM/MS/0.0125CM CELLS

TIME .0000

/TABLE/PR7/R4A/BRITISH HE INIT/COMP B/STEEL/0.05CM/MS/0.0125CM CELLS

Fig. 3. Interface plots from the three-dimensional calculation for the y z plane (top) and the x z plane (bottom) at 0 (left) and 5 μ s (right).

TIME 10.0009
/TABLE/PR7/R4A/BRITISH HE INIT/COMP B/STEEL/0.05CM/MS/0.0125CM CELLS

TIME 10.0009
/TABLE/PR7/R4A/BRITISH HE INIT/COMP B/STEEL/0.05CM/MS/0.0125CM CELLS

TIME 15.0057
/TABLE/PR7/R4A/BRITISH HE INIT/COMP B/STEEL/0.05CM/MS/0.0125CM CELLS

TIME 15.0057
/TABLE/PR7/R4A/BRITISH HE INIT/COMP B/STEEL/0.05CM/MS/0.0125CM CELLS

Fig. 4. Interface plots from the three-dimensional calculation for the yz plane (top) and the xz plane (bottom) at 10 (left) and 15 μ s (right).

TIME 20.0099

/TABLE/PR7/R4A/BRITISH HE INIT/COMP B/STEEL/0.05CM/MS/0.0125CM CELLS

TIME 20.0099

/TABLE/PR7/R4A/BRITISH HE INIT/COMP B/STEEL/0.05CM/MS/0.0125CM CELLS

TIME 25.0022

/TABLE/PR7/R4A/BRITISH HE INIT/COMP B/STEEL/0.05CM/MS/0.0125CM CELLS

TIME 25.0022

/TABLE/PR7/R4A/BRITISH HE INIT/COMP B/STEEL/0.05CM/MS/0.0125CM CELLS

Fig. 5. Interface plots from the three-dimensional calculation for the y z plane (top) and the x z plane (bottom) at 20 (left) and 25 μ s (right).

Fig. 6. Total energy, kinetic energy, and internal energy of the projectile, sabot, and target as a function of time.

localized and may not provide sites for initiation of the HE. However, the edge of the casing plug sheared off by the projectile does contact the HE. Plastic work in this material results in values of maximum internal energy of $\sim 4.0 \times 10^{-3}$ Mbar cc/g. Assuming a heat capacity of the steel casing of 4.6×10^{-6} Mbar cc/g k (0.46 J/g k), the maximum temperature rise of this material is ~ 870 k. Heat transfer by conduction is not included in the calculation so that energy is not transferred from the casing to the HE in this manner. Thus, actual temperatures of HE flowing past this region may be higher than indicated above (see DISCUSSION section).

Figure 9 shows a plot of pressure as a function of time for the first few microseconds at the positions of three Lagrangian tracer particles located on the z axis ($x = y = 0$). The particle at $z_0 = 0.15$ cm was initially at the casing-HE interface; the other two particles were in the HE. It is interesting that material from all three locations shows extended periods of zero pressure (it was assumed that the HE could not support negative pressures). This would indicate that cracking and separation of the HE could occur as rarefactions follow the initial shock. Fracture was not modeled in this calculation so that no estimates of HE damage are available.

Fig. 7. Kinetic energy (top) and internal energy (bottom) of the system components as a function of time.

Fig. 8. Maximum internal energy and pressure of the HE in the target as a function of time.

Fig. 9. Pressure as a function of time for three Lagrangian tracer particles along the z axis.

HE just behind the casing and in the path of the projectile must flow out of the way as the projectile penetrates. This flow can be seen in Fig. 10, which shows velocity vectors in the y-z plane (top) and x-z plane (bottom) at 25 μ s, with a velocity offset such that the projectile is essentially stationary. In effect, these views show velocity vectors as seen by an observer riding at the front of the projectile/casing plug. The flow of HE around the projectile is evident.

Another sense of the motion of the HE can be seen from the paths followed by Lagrangian tracer particles. Figure 11 shows plots of the locations of tracer particles that were initially located in the HE just behind the cladding. Figure 11, top, shows particle paths that stay in the y-z plane; the particle initially at $y = 0.3$ cm is at the HE-polycarbonate interface. Figure 11, bottom, shows particle paths that stay in the x-z plane. In both plots, the dashed lines connect locations at specific times. By 30 μ s, the inside surface of the cladding at $x = y = 0$ has been pushed from its initial location ($z = 0.15$ cm) to $z = 1.14$ cm. The tracer particle on the z axis remains there. The other particles get pushed to the side as the projectile moves in.

Figure 12 shows a plot of specific internal energy (e) at the locations of two tracer particles initially in the path of the projectile. The initial pulse at ~ 1 μ s is the shock from the projectile impact. There is a steady rise in e as this material flows around the incoming projectile (2 to ~ 20 μ s). The value of e for the material associated with the particle in the x-z plane (dashed curve in Fig. 12) levels off to some extent after 20 μ s. By 20 μ s, this material has been diverted to one side and is now flowing approximately parallel to the z axis (see Fig. 10, bottom and Fig. 11, bottom). This condition would indicate that most of the plastic work occurs as the material is diverted to one side by the incoming projectile. The value of e for the material associated with the particle in the y-z plane (solid curve in Fig. 12) shows a similar rise up to ~ 15 μ s, but a more complex behavior at later time. This material is being forced into the space between the projectile and polycarbonate block by ~ 20 μ s (see Fig. 10, top and Fig. 11, top).

TWO-DIMENSIONAL CALCULATIONS

Two two-dimensional calculations, one of the x-z plane and one of the y-z plane, were done before the three-dimensional calculation to provide preliminary information about the timing of the impact and the resulting damage. Figure 13 shows interface plots from the y-z plane calculation (top) and the x-z plane calculation (bottom) at 10 μ s (left) and 20 μ s (right). The 10- μ s result is similar to the three-dimensional result at that time (Fig. 4 left), except that there is somewhat more lateral deformation of the polycarbonate block near the casing in the y-z plane (top plots). The 20- μ s result (Fig. 13 right) shows larger differences when compared with the three-dimensional result at that time (Fig. 5 left). There is considerably more lateral deformation of the polycarbonate block in the y-z plane in the two-dimensional calculation (top plots). There is also more deformation of the casing into the HE in the x-z plane in the two-dimensional calculation at this time (bottom plots).

TIME 25.0022

/TABLE/PR7/R4A/BRITISH HE INIT/COMP B/STEEL/0.05CM/MS/0.0125CM CELLS

LOCAL MAX 8.223E-02

GLOBAL MAX 8.226E-02

SCALED VEC 8.000E-02

TIME 25.0022

/TABLE/PR7/R4A/BRITISH HE INIT/COMP B/STEEL/0.05CM/MS/0.0125CM CELLS

LOCAL MAX 7.835E-02

GLOBAL MAX 7.835E-02

SCALED VEC 8.000E-02

Fig. 10. Velocity vectors (with a velocity offset such that the projectile is essentially stationary) in the y-z plane (top) and the x-z plane (bottom) at 25 μ s.

Fig. 11. Flow paths of Lagrangian tracer particles in the HE in the y-z plane (top) and the x-z plane (bottom).

Fig. 12. Internal energy as a function of time for two tracer particles in the HE.

Figure 14 shows plots of pressure as a function of time at Lagrangian tracer particle locations on the z axis ($x = y = 0$) at $z_0 = 0.15$ cm (top) and $z_0 = 0.8$ cm (bottom). The three curves show pressure from the three-dimensional calculation and the two two-dimensional calculations. At $z_0 = 0.15$ cm (at the inside surface of the casing), the three calculations show similar peak pressures (from the initial shock), but the three-dimensional result decays faster. At $z_0 = 0.80$ cm, the peak pressure from the initial shock in three-dimensional calculation is only about half the two-dimensional peaks. Again, the pressure from the three-dimensional calculation decays faster.

All these differences are related to the inherent assumption in the two-dimensional calculations that the projectile and target are slabs in the direction normal to the plane of the calculation. This situation does not allow the flow of material in that direction, forcing more deformation and higher pressures in the two remaining directions.

DISCUSSION

The three-dimensional calculation indicates that the HE is not strongly confined in this experiment, primarily due to the lateral expansion of the polycarbonate blocks during the impact. There is also some expansion of the casing in the radial direction.

INTERFACES

time 10.0429

u/p7/hun2a/roberts exp/top view/2d/planer/0.0125cmel/0.05cm/ms

INTERFACES

time 10.0316

u/p7/hun2a/roberts exp/2d/planer/0.0125cmel/0.05cm/ms

INTERFACES

time 20.0022

u/p7/hun2a/roberts exp/top view/2d/planer/0.0125cmel/0.05cm/ms

INTERFACES

time 20.0409

u/p7/hun2a/roberts exp/2d/planer/0.0125cmel/0.05cm/ms

Fig. 13. Interface plots from the two-dimensional calculation in the y z plane (top) and the x z plane (bottom) at 10 (left) and 20 μ s (right).

Fig. 14. Pressure as a function of time for Lagrangian tracer particles on the z axis ($x = y = 0$) at $z_0 = 0.15$ cm (top) and $z_0 = 0.8$ cm (bottom) for the three-dimensional calculation and two two-dimensional calculations.

One feature that was looked for, but was not seen in the calculation, was a flow of HE out of the hole in the casing. The rapid ejection of HE from the casing could result in strong velocity gradients and shear flows that heat the HE (Frey 1981, Dienes 1986). There are three factors that tend to keep the HE inside the casing. First, the projectile has a length/diameter ratio of ~ 3 ; during the calculation there is still projectile material filling the hole in the casing and blocking the outflow of HE. A shorter projectile might have allowed HE to flow out of the casing. Secondly, the lateral expansion of the polycarbonate blocks relieves pressure on the HE so that there is less tendency for it to be ejected from the casing. Third, the sabot impacts the polycarbonate blocks and casing between 15 and 20 μs , filling any holes around the periphery of the projectile.

There are hints from these calculations of how initiation of a homogeneous sample of HE might occur in the experiment. The first involves the reshock of a small amount of HE at $\sim 20 \mu\text{s}$ (see Fig. 8). This behavior is strongly dependent on the details of deformation of the projectile, casing, polycarbonate, and sabot. Small changes in dimensions of the components or misalignment of the projectile and target could eliminate or enhance this phenomenon. The second involves the heating of the HE from plastic work during the impact. The maximum temperature rise of the HE (exclusive of the small region that was reshocked) was $\sim 80 \text{ k}$. However, this temperature rise comes from the average temperature of a region the size of a computational cell, and phenomena such as shear bands or cracks could result in higher temperatures on a smaller scale than the cell size (Frey 1981, Dienes 1986).

The third potential HE initiation mechanism involves heating of the HE from contact with the casing material. Localized shock heating of various parts of the casing occurs throughout the calculation. However, this material may not contact the HE. Plastic work at the edge of the casing plug sheared off by the projectile results in a temperature rise of $\sim 870 \text{ k}$ in that region. This material does contact the HE. The lack of heat transfer by conduction in the calculation means that temperatures of HE near this casing material may be lower than actually occur. An estimate of the transient temperature distribution in HE (initially at 380 k) that contacts steel (initially at 1170 k) was made from a simplified analysis of heat transfer by conduction in two materials that come into contact (Carslaw and Jaeger 1959). Steel was assumed to have a thermal conductivity of 0.54 J/cm s k , and a thermal diffusivity of $0.15 \text{ cm}^2/\text{s}$. HE was assumed to have a thermal conductivity of 0.0022 J/cm s k , and a thermal diffusivity of $0.0011 \text{ cm}^2/\text{s}$. Figure 15 shows a plot of temperatures in the HE as a function of distance from the HE/steel interface at 1 and 10 μs . There is little penetration of heat into the HE on a 1- μs time scale. After $\sim 10 \mu\text{s}$, high temperatures have penetrated only a few microns into the HE. The poor thermal conductivity and thermal diffusivity of HE are the cause of this behavior. This very approximate analysis indicates that only thin layers of HE would be heated as it flows over the hot steel casing. However, prolonged contact could heat the HE well above initiation temperatures.

Fig. 15. Temperature of HE (initially at 380 k) in contact with steel (initially at 1170 k) as a function of distance from the HE/steel interface at 1 and 10 μ s.

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