Perforation of HY-100 Steel Plates with Long Rod Projectiles

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Abstract

We conducted perforation experiments with 4340 steel, rod projectiles and HY-100 steel, target plates at striking velocities between 80 and 370 m/s. Projectiles were machined to nominally 30-mm-diameter and 281-mm-length so they could be launched from a 30-mm-powder gun without sabots. The target plates were rigidly clamped at a 305-mm diameter and had a nominal thickness of 10.2 mm. In addition to measuring striking and residual projectile velocities, we obtained back surface framing camera data that showed clearly the plate deformation and plug ejection process. An Imacon 792 camera provided up to 20 frames per experiment with an interframe time duration of 10 μ s. Our modeling work is in progress, but we present a beam model that exhibits the features observed in the experiments.

Introduction

We conducted a series of perforation experiments to investigate the ballistic performance of HY-100 steel plates. The experiments were instrumented with diagnostics that provided striking velocity, impact time, and residual velocity. In addition, an Imacon 792 camera photographed the rear surface deformation and plug ejection of the plate. At this time, we have not completed the analytical model for the

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plate deformation (bending) and plug ejection (shear localization), but we present a beam model that contains these observed features.

Perforation Experiments

We performed a set of perforation experiments with 4340 steel rod projectiles that impacted 10.4-mm-thick HY-100 steel (MIL-S-16216J-AM#1) plate targets at normal incidence. The rods were machined to fit in a 30-mm-diameter powder gun and launched without sabots. The rods had nominal 281-mm-length and 1.58-kg-mass.

Several machining steps were performed on the plates in preparation for testing. The plates were blanchard ground on both surfaces to provide a smooth, slag-free, flat surface. Eight equally spaced 22.2-mm-diameter holes were drilled on a 381-mm-diameter bolt circle to allow the plates to be sandwiched between, and bolted to, the test fixtures. The plates were installed with a clamping system that had an inner clamp diameter of 305mm.

We varied the striking velocity, V_s , between 78m/s and 370m/s. Table 1 shows the shot parameters and test results for the 10.4-mm-thick HY-100 plates. Figure 1 shows that this range of striking velocities determined accurately the ballistic limit velocity V_{bl} and the residual rod velocities V_r .

Table 1: Shot parameters.

Shot #	$M_{pr}(kg)$	$h(mm)$	$V_s(m/s)$	$V_r(m/s)$	$V_p(m/s)$	$\phi(mm)$	$M_{pl}(kg)$
1-0149	1.594	10.5	78	0	0	0	0.000
1-0179	1.558	10.5	82	0	0	0	0.000
1-0194	1.559	10.5	105	0	0	0	0.000
1-0196	1.557	10.5	114	0	0	0	0.000
1-0195	1.558	10.4	125	80	80	30.5	0.054
1-0176	1.557	10.5	126	84	104	30.5	0.055
1-0148	1.583	10.5	127	98	112	30.3	0.056
1-0147	1.583	10.2	162	142	164	30.5	0.056
1-0178	1.556	10.5	163	138	163	30.7	0.057
1-0175	1.556	10.4	165	141	163	30.7	0.057
1-0191	1.558	10.5	207	168	210	31.1	0.059
1-0146	1.582	10.5	258	232	268	31.2	0.066
1-0192	1.558	10.4	261	233	269	31.8	0.064
1-0177	1.559	10.5	263	234	273	31.8	0.065
1-0180	1.559	10.5	318	284	335	32.6	0.063

1-0193	1.557	10.5	322	289	335	32.6	0.067
1-0145	1.582	10.2	370	333	389	33.1	0.062

h = plate thickness, V_s = striking velocity, V_r = rod residual velocity,
 V_p = plug residual velocity, ϕ = hole diameter, M_{pr} = projectile mass,
 M_{pl} = plug mass after perforation.

Figure 1: Rod striking velocity versus rod residual velocity data.

Striking velocity was determined by the rod interrupting two continuously monitored laser beams during free-flight prior to striking the plate. Impact time was measured by a time-of-arrival gage cemented to the front surface of the plate. The signal from the time-of-arrival gage triggered the Imacon 792 camera that monitored the rear surface of the plate. The first frame in Figures 2 and 3 is at $5\mu\text{sec}$ from impact with all subsequent frames at $10\mu\text{sec}$ intervals. Figures 2 and 3 show the rear surface deformation recorded by the Imacon camera for shots 1-0191 ($V_s=207$ m/s) and 1-0193 ($V_s=322$ m/s) respectively. A fiducial length was placed behind the rear surface of the plate to provide a known length scale. The photographs show the early time

plate deformation and late time plug ejection. We also see a cloud of material forming just after plug ejection. We believe this to be a combination of the time-of-arrival gage and compressed air that are trapped between the rod and the plate at the time of impact.

Residual velocity was determined by the plug and rod combination exiting the rear surface of the plate and interrupting two continuously monitored laser beams during free-flight.

Figure 2: Dynamic deformation of rear surface of plate showing bending and plug ejection; $V_s=207$ m/s.

Figure 3: Dynamic deformation of rear surface of plate showing bending and plug ejection; $V_s=322$ m/s.

Beam Model

The photographs in Figures 2 and 3 led us to conclude that the major mechanisms for plate perforation are plate bending and shear localization. To start our modeling, we consider the simpler beam perforation problem. We start with the rigid plastic beam analysis presented by Jones [1] and Symonds [2] and extend their results to predict ballistic limit velocity V_{bl} and residual velocity V_r . We model an infinitely long beam with rectangular cross-section struck by a rigid rod (nondeforming) with rectangular cross-section. Figure 4 defines the problem geometry.

Figure 4: Geometry of the problem. The rod and beam have width b into the page.

Following the rigid plastic beam analysis of Symonds [2], we take the velocity profiles shown in Figure 5 as

$$\dot{w} = \dot{W}_0 \quad -a \leq x \leq 0 \quad , \quad (1a)$$

$$\dot{w} = \dot{W}_1 \left(1 - \frac{x}{\lambda} \right) \quad 0 \leq x \leq \lambda \quad , \quad (1b)$$

$$\dot{w} = 0 \quad x > \lambda \quad . \quad (1c)$$

Figure 5: Diagram of velocity distribution.

We now write the equations of dynamics for the beam section $-\lambda < x < \lambda$. There are fully plastic moments, M_o , at $x = \pm\lambda$ while the shear forces, Q_o , are zero at $x = \pm\lambda$. The equation for lateral momentum is

$$(G + 2am)\ddot{W}_0 + 2 \int_0^\lambda m \ddot{w} dx = 0 \quad , \quad (2)$$

where G is the mass of the rod and m is the mass per unit length of the beam. The equation for angular momentum of the beam section $0 < x < \lambda$ is

$$2M_o = \int_0^\lambda m \ddot{w} x dx \quad . \quad (3)$$

The equation for the lateral momentum of the rod and plug is

$$(G + 2am)\ddot{W}_0 = -2Q_o \quad . \quad (4)$$

We integrate these equations subject to the initial conditions $\dot{W}_0(t=0) = V_s$, $\dot{W}_1(t=0) = 0$, $W_1(t=0) = 0$, and $W_o(t=0) = 0$. After some mathematical manipulations we obtain

$$W_o(t) = \frac{GV_s t}{G + 2am} - \frac{Q_o t^2}{G + 2am} \quad , \quad (5)$$

$$W_1(t) = \frac{Q_o^2 t^2}{6mM_o} \quad , \quad (6)$$

$$\lambda = \frac{6M_o}{Q_o} \quad . \quad (7)$$

For a Tresca yield criterion with tension yield stress σ_o , the plastic bending moment and shear force are

$$M_o = \frac{bh^2\sigma_o}{4} \quad , \quad Q_o = \frac{bh\sigma_o}{2} \quad . \quad (8a,b)$$

The rod perforates the beam when

$$W_o(t_p) - W_1(t_p) = h \quad , \quad (9)$$

with residual rod velocity

$$V_r = \dot{W}_o(t_p) \quad , \quad (10)$$

where t_p is defined as the time of perforation.

Figures 6a,b illustrate the displacement and velocity versus time histories for $V_s = V_{bl}$. When $V_s = V_{bl}$ we satisfy the conditions for perforation: $W_o - W_1 = h$ and $\dot{W}_o = \dot{W}_1$ at $t = t_p$. If the striking velocity is less than V_{bl} , then the condition $\dot{W}_o = \dot{W}_1$ is reached before $W_o - W_1 = h$ and the plate will not be perforated. For striking velocities higher than V_{bl} the plate will be perforated and the condition $\dot{W}_o > \dot{W}_1$ will hold. For all $V_s \geq V_{bl}$, the residual rod/plug velocity is

$$V_r = \dot{W}_o(t_p) \quad . \quad (11)$$

We note that at the ballistic limit ($V_s = V_{bl}$) the residual velocity is finite. This result is observed experimentally in Figure 1. From equations 5,6,8, and 9 the ballistic limit velocity is

$$V_{bl}^2 = \left(1 + \frac{2am}{G}\right)^2 \frac{2bh\sigma_o}{3m} \left[1 + \frac{3mh}{G + 2am}\right] \quad . \quad (12)$$

For long rod penetrators and thin plates the term $2am/G$ is small compared to unity and may be neglected. The ballistic limit velocity for long rods and thin plates is

$$V_{bl}^2 \equiv \frac{2bh\sigma_o}{3m} + \frac{2bh^2\sigma_o}{G} \quad (13)$$

Figure 6: (a) Displacement versus time profile for $V_s = V_{bl}$.

Figure 6: (b) Velocity versus time profile for $V_s = V_{bl}$.

Summary

We conducted a series of perforation experiments with 4340 steel rod penetrators perforating HY-100 steel plates and present a

beam model that includes bending and shear localization. The beam model predicts a non-zero residual velocity at the ballistic limit velocity which is in agreement with our experimental observation for plates.

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References

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