ON THE OPTIMAL PERFORMANCE OF LONG-ROD PENETRATORS SUBJECTED TO TRANSVERSE ACCELERATIONS

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Abstract—The paper deals with theoretical considerations on the conception and optimization of long-rod penetrators with regard to bending strain and penetration efficiency. In a first step we describe a method allowing to design long penetrators in such a manner that given values of bending stress and deflection are met if the rods are subjected to lateral forces. On the assumption of a constant lateral acceleration this results in rods with various dimensions; the aspect ratio remarkably does not remain constant. Then these penetrators are examined for maximum penetration efficiency while considering rods of equal energy. For the case studied the procedure results in an optimum velocity of about 2700 m/s. This demonstrates a fundamental difference in comparison to the optimization process with L/D-scaled penetrators where a much lower optimum velocity (2300 m/s) is obtained. In comparison to the reference penetrator (L/D=34, v=1800 m/s) the optimum penetrator – still at constant stress level and at an impact velocity of 2700 m/s – has of course a reduced mass, but also a reduced length and diameter showing an aspect ratio of 40. The perforation power could be increased by some 17%. On the other hand, the linearly scaled penetrator at constant energy only shows an increase of about 7% in penetration capability if the impact velocity reaches its optimum value at 2300 m/s. The optimization procedure of the energy-efficient penetration of constant-stress projectiles leads to an optimal velocity well in the hypervelocity regime. Furthermore, the special design of the penetrators with constant stress level results in a gain of penetration efficiency. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Theory, long-rod penetrators, high fineness ratio, structural integrity, transverse accelerations, lateral forces, bending, rods with constant bending stress, penetration efficiency.

INTRODUCTION

During the last decades the requirement of a steadily increasing perforation power and the need to defeat different target types have resulted in quite sophisticated kinetic-energy long-rod penetrators. These rods show relatively high aspect ratios because of the physical parameters ruling the perforation power: density and length of the projectile as well as striking velocity at the target.

Now, modern penetrator materials do already have a very high density that can scarcely be increased further; on the other hand, in order to achieve high muzzle velocities, it is necessary to get low launch package masses. For a penetrator with great length this results in relatively small diameters and hence high fineness ratios.

As a protection measure against this threat quite a number of targets with special interaction processes were brought into discussion with the aim to break these slender cylinders into pieces; this might be done by construction parameters concerning the target or by any other special procedure related to active or reactive protection. In fact this seems to be a very effective method to defeat the penetrator as it is well known that these slender rods quite often fail because of severe
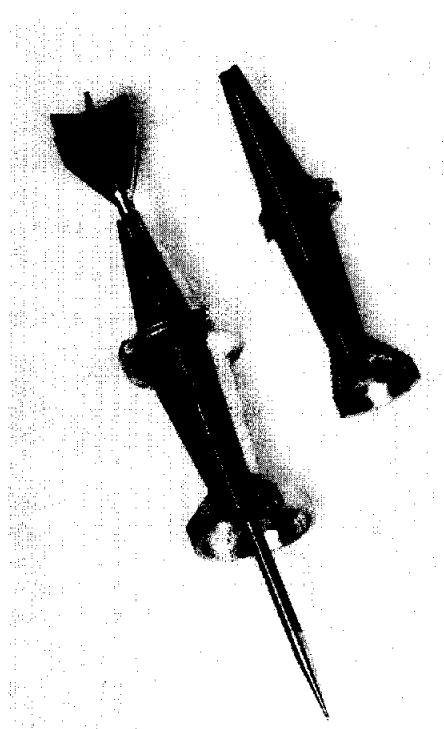
Fig. 3. Long-rod projectile in free flight showing severe bending.
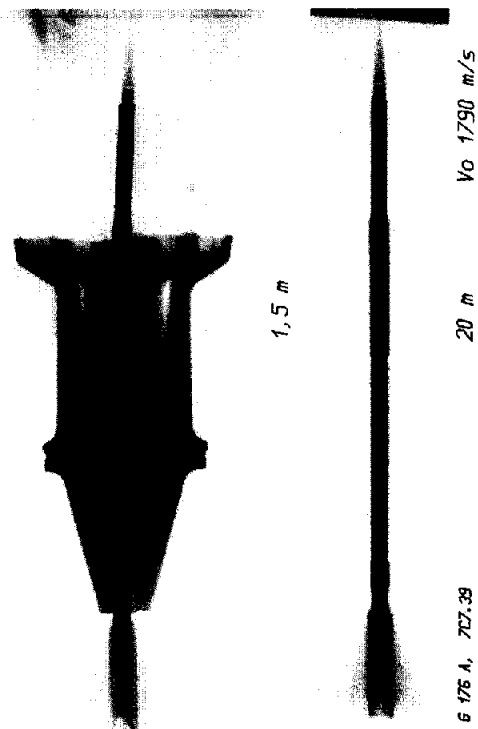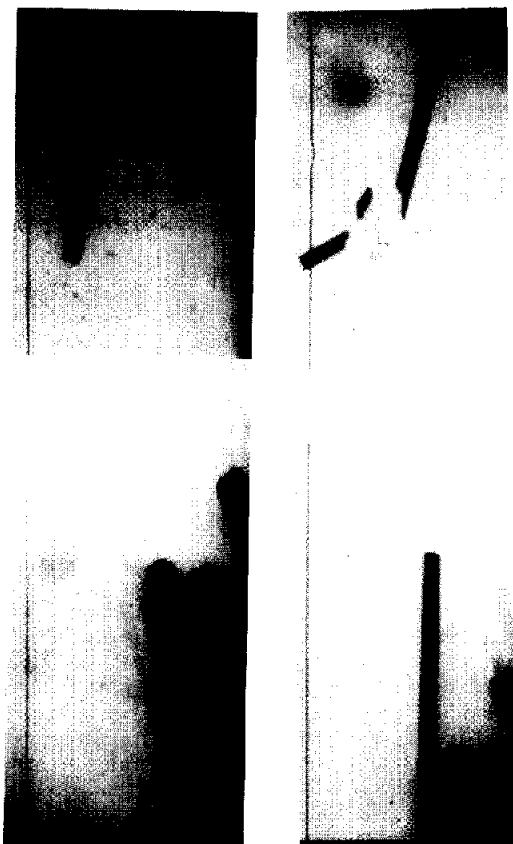
V_0 1710 m/s

20 m

6 176 A, 7C7.38

Fig. 4. Bending effects (above) and fracture (below) affecting
long rods caused by interaction with moving plate.

Fig. 1. Long-rod projectile, cal. 40 mm, L/D=40.

1,5 m

V_0 1790 m/s

20 m

6 176 A, 7C7.39

Fig. 2. Long-rod projectile, sabot separation; free flight.

structural integrity and stability problems during the acceleration and flight phase and of course, even more during penetration if strained by lateral forces.

Keeping this situation in mind, it seems useful to discuss possible ways of hardening the projectile against this special threat of transverse forces and to examine whether an optimal design for a penetrator can be found in terms of stress, energy and striking velocity.

EXPERIMENTS WITH RODS OF HIGH FINENESS RATIO

As already mentioned, long-rod penetrators often show stability and integrity problems during the acceleration and flight phase. Model-scale experiments with subcalibre projectiles made of tungsten heavy metal with diameters of 6 mm and aspect ratios of 40 (figure 1) demonstrate these effects. As an example of such an experiment a flexure of the penetrator at 1.5 m off the muzzle is clearly visible (figure 2, upper part). About 20 m downstream no flexure is apparent in that photograph any longer. Figure 3 shows another experiment with a strong flexure in the later flight phase.

It is obvious that stability problems such as buckling, bending or bending vibrations are all the more likely as the fineness ratio of the projectile is high [1, 2]. In general, this will result in a loss of efficiency or even fracture of the projectile. During the target interaction process these projectiles also bear extreme loads. This is even more evident during the penetration of those types of targets which exercise a transverse load on the rod. Two examples of such projectile-target interactions are shown in figure 4 with a bended penetrator and broken one, respectively.

Dealing with the penetration behaviour of rod-shaped penetrators, the characteristic measures usually taken are mass, length and diameter as well as the fineness ratio, i.e. the L/D-quotient. The latter quantity is the determining projectile shape factor and therefore is commonly used as a group parameter in many of the well-known graphs.

The aspect ratio is certainly a suitable reference parameter when one looks at the comparison of the perforation power of scaled and full-scale experiments. For instance, by using the Cranz Scaling Law the penetration power of rods with different dimensions can easily be estimated by the same scaling factor [3]. Furthermore, there are some special transformation rules for penetrators with constant L/D-ratios concerning some generally valid scaling laws [4, 5]. However, neither these rules nor the aspect ratio give any hint on how to improve on the integrity problems mentioned above, so that it seems useful to have a closer look at the penetrator strain.

REFLECTIONS ON ROD/TARGET INTERACTION

A Simple Hypothesis: Bending Rod with Uniform Transverse Load

Modern targets against long-rod penetrators quite often integrate a target plate motion, so that a very strong interaction between penetrator and target leads to the fragmentation of the rod. This effect is apparent in experiments and leads to the assumption that the penetrator is mainly stressed by bending forces.

In order to get a simple but generally valid description, we continue by assuming a working hypothesis that considers the penetrator to be a bending rod with a uniform transverse load. It is to be hoped that this then leads to a more universally applicable insight and perhaps also to simple transformation or scaling rules for penetrators of different shapes.

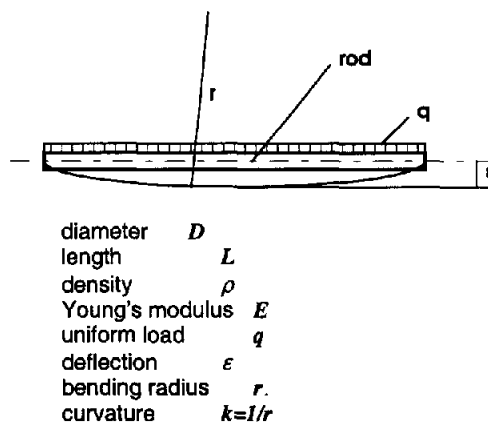|	
diameter	D
length	L
density	ρ
Young's modulus	E
uniform load	q
deflection	ε
bending radius	r.
curvature	$k=1/r$

Fig. 5. Cylindrical rod, uniform bending load.

If we are interested in a general description of a bending rod it does not really matter which special bending case we look at. For the time being we consider the bending rod to be a prismatic body of circular cross-section (figure 5). This restriction simplifies the description of our problem without any loss of generality. Even more, looking at modern rod penetrators with high aspect ratios, this assumption is not very far from reality or can easily be converted into the shape under consideration, even for penetrators not showing cylindrical cross-sections.

The rod of diameter D and length L is supported at both ends and carries a uniform transverse load. The moment thus induced results in a bending of the rod with a radius r. The quantity ε denotes the maximum elongation.

For the load condition of the bending column as depicted in figure 5 the following equations are valid in detail [6, 7, 8, 9]:

The bending moment is

$$M = q \cdot L^2 / 8 \ .$$

Then, in order to calculate the maximum stress we have the moment of resistance

$$W = \frac{I}{D/2} \ ,$$

where I stands for the areal moment of inertia, so that

$$I = \pi \cdot D^4 / 64 \ .$$

Now let us look at the acting bending forces which, for the most part, are considered to be external forces. As it does not seem evident to define an acting force in our case of penetrator and target-interaction, we assume that the uniform transverse load is induced by the rod proper weight, i.e. it is caused by lateral acceleration only. Then, with Newton's Law we can calculate the total load as:

$$F = \pi / 4 \cdot D^2 \cdot L \cdot \rho \cdot a_q \ .$$

Herein we define the transverse acceleration a_q as a multiple of the normal acceleration g due to gravity, i.e. $a_q = n \cdot g$. Thereby it is possible to correlate the load in a very simple manner with the transverse acceleration of the rod during the penetration of a target. In fact, this description seems to be very close to reality, on the assumption that the interacting penetrator masses do not differ too much from each other.

Then, given $q = F / L$, the load per unit length on the rod is calculated to be

$$q = \pi / 4 \cdot D^2 \cdot \rho \cdot a_q \ .$$

Now, the general expression for the bending stress in the case of a rod under uniform transverse load is written as

$$\sigma_B = \frac{q \cdot L^2}{8 \cdot W} \ .$$

With the above-mentioned expressions this leads to

$$\sigma_B = \rho \cdot a_q \cdot \frac{L^2}{D} \ .$$

Here it might be convenient to take the well-known aspect ratio *L/D* as an intermediate parameter. This results in the expression

$$\sigma_B = \rho \cdot a_q \cdot \left(\frac{L}{D} \cdot L \right).$$

The <u>maximum pitch of deflection sag</u> is defined by

$$\varepsilon = \frac{5}{384} \cdot \frac{q \cdot L^4}{E \cdot I} \quad ,$$

and with the above equations can be written as

$$\varepsilon = \frac{5}{24} \cdot \frac{\rho \cdot a_q}{E} \left(\frac{L}{D} \cdot L \right)^2 .$$

Finally, the <u>curvature</u> of the transversely loaded rod is given by the general equation

$$k = \frac{M}{E \cdot I} \quad ,$$

which can easily be transformed into

$$k = 2 \cdot \frac{\rho \cdot a_q}{E} \cdot \left(\frac{L}{D} \right)^2 .$$

PENETRATORS OF CONSTANT BENDING STRESS

Rods at Transverse Accelerations

We are now presuming that the rods under consideration are made of the same material and undergo the same transverse accelerations. If we then compare rods of different dimensions, it becomes evident that the factors $\rho \cdot a_q$ and $\frac{\rho \cdot a_q}{E}$ remain unchanged. The recurring expression $\frac{L}{D} \cdot L$ will now be designated as f_L because the length as the predominant measurement is also the quantity defining its dimension. Furthermore, it makes sense to write that expression in such a form as to show up well-known quantities like the fineness ratio and the diameter. We then get

$$f_L = \frac{L}{D} \cdot L = \frac{L}{D} \cdot \frac{L}{D} \cdot D = \left(\frac{L}{D} \right)^2 \cdot D \ .$$

The equations for bending stress, maximum deflection and curvature may now be expressed in the following form:

<u>Bending stress:</u>

$$\sigma_B \sim \left(\frac{L}{D} \cdot L \right) = \left(\frac{L}{D} \right)^2 \cdot D = f_L . \tag{1}$$

Maximum pitch of deflection sag:

$$\varepsilon \sim \left(\frac{L}{D} \cdot L\right)^2 = \left(\frac{L}{D}\right)^4 \cdot D^2 = f_L^2 \ .$$

Curvature:

$$k \sim \left(\frac{L}{D}\right)^2 .$$

Now, for homogeneous rods which are made of the same material and undergo the same transverse accelerations we can draw the following conclusions:
If the dimensions of the rods are chosen in such a way that

$$\boxed{f_L = L^2/D = (L/D)^2 \cdot D = const.} \ ,$$

then by identical transverse acceleration these rods bear a different load, indeed, but they show

* Identical maximum bending stress
and
* Identical pitch of deflection sag.

It should be pointed out that this is quite an interesting aspect as far as conception and construction are concerned; this is also true for interior ballistics, and especially the terminal ballistics of long-rods.

Fig. 6.   Sketch of bended rods; $f_L = const.$; diameter ratio: 2:1.

Figure 6 gives an impression of the bending behaviour of two rods designed according to the f_L-rule. We get identical deflection; with a diameter ratio of 2, the length only increases by the factor of $\sqrt{2}$.

On the other hand, taking the criterion

$$\boxed{\lambda = L / D = const.}$$

as a construction rule, i.e. we treat geometrically similar rods, then these penetrators show

* Identical curvature of bending

when charged by a 'proper weight'. This means, figuratively speaking, that rods with identical aspect ratios charged by the same amount of transverse acceleration do all fit into the same curvature model, whereas bending stress and elongation grow even more than proportionally as a function of the L/D-ratio (see figure 7).
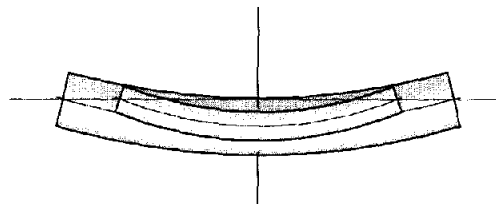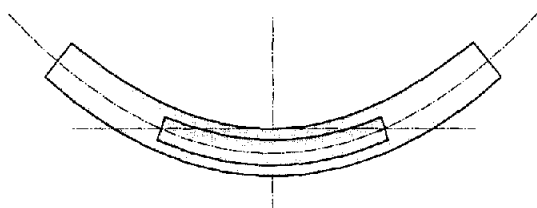

Fig. 7.   Sketch of bended rods; $\lambda = const.$; diameter ratio: 2:1; the small rod is identical to the one in figure 6.

Comparison between Rods of Constant (L/D) and Constant $(L/D) \cdot L$

We shall have a quick look at penetrators defined by the above-mentioned parameter

$$f_L = (L/D)^2 \cdot D = const.$$

in comparison to penetrators following the 'classical' rule of fineness ratio, i.e.

$$\lambda = L / D = const.$$

As a reference projectile we take a rod with a 25 mm diameter and a length of 850 mm. Then the values for f_L and λ are calculated to be $f_L = 28,9 \ m$ and $\lambda = 34$.

For the further calculations we consider the density of the rod to be 17500 kg/m³; Young's modulus is fixed at 350 MPa and the transverse acceleration at a hundred times the gravitational acceleration. Then for all penetrators scaled according to the f_L-parameter these data result in the same maximum bending stress of 484 MPa.
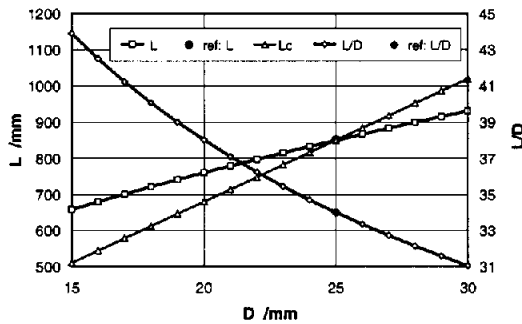

Fig. 8.   Length and aspect ratio vs. diameter for rods of constant stress (f_L=const.=28,9 m) and constant aspect ratio (λ=const.=34); length Lc.

The diagram (figure 8) shows the two parameters – length L (squares) and aspect ratio L/D (diamonds) – for penetrators of different diameters but corresponding to the criterion f_L=const. (=28.9 m). Black circle and black diamond stand for the length and the L/D-ratio of the reference projectile. For comparison the length L_c (triangles) is also depicted for penetrators according to the condition λ=const. (The parallel line to the abscissa for L/D=const.=34 including the black diamond is not shown.)

The following tendencies are apparent: with an increasing diameter the length L of the penetrators corresponding to the new parameter is much less increasing than the corresponding value L_c for geometrically similar projectiles; as an example the length of the projectile of equal aspect ratio simply doubles, of course, when diameters change from 15 mm to 30 mm, whereas the projectile of equal stress only increases by some 40% in length. Hence the L/D-ratio of these rods decreases with the increasing penetrator diameter. According to the assumptions the graph shows coinciding values for lengths (black circle) and aspect ratios at D=25 mm (black diamond).

PENETRATORS OF EQUAL BENDING STRESS AND ENERGY

The diagrams depicted above show the features of penetrators as a function of diameter according to the parameter f_L=const. without any further restriction. Generally, designing projectiles requires that special conditions should be observed such as limitations in available energy or demands for optimal ballistic performances, for instance.

Here we look at the properties of rods by taking into account the additional condition of a constant kinetic energy. Then the quantities D, L and v can no longer be chosen independently but have to satisfy the following relation

$$E = const. = 1/2 \cdot m \cdot v^2 .$$

This leads to

$$E = 1/8 \cdot \pi \cdot \rho \cdot D^2 \cdot L \cdot v^2$$

and finally

$$L = (8 \cdot E)/(\pi \cdot \rho) \cdot 1/(D^2 \cdot v^2) .$$

If we put

$$f_E = (8 \cdot E)/(\pi \cdot \rho) ,$$

then we obtain the generally valid equation

$$L = f_E \cdot 1/(D^2 \cdot v^2) .$$

Here we have to introduce the special condition for f_L. With a transformation, so that the parameter f_L is written as $L^2/D = const.$, we finally get

$$L = f_E^{1/5} \cdot \left(\frac{L^2/D}{v} \right)^{2/5} .$$

(2)

Thus all quantities for the calculation of the penetrator data are known.

The graph of figure 9 shows some important projectile quantities as a function of velocity according to the parameter $f_L = const.$ and at constant projectile energy; again, the data are calculated in relation to the reference projectile at a velocity of 1800 m/s. As compared with the condition $\lambda = const.$, the data for the relative length (in that case coinciding with the relative diameter) are also given.
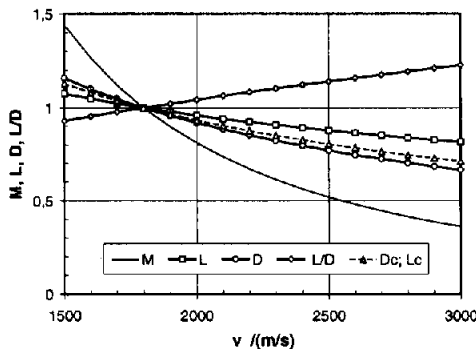
For all rods increasing velocities lead to lower values for mass, length and diameter. As compared with the variant $\lambda = const.$, then for $f_L = const.$ the length decreases less and the diameter more, which results in higher projectile aspect ratios for increasing velocities.

Fig. 9. Relative values: mass, length, diameter and aspect ratio vs. velocity at constant energy for rods of $f_L = const.(28,9)$ and $\lambda = const.(34; Dc, Lc)$.

OPTIMAL PENETRATION EFFICIENCY FOR RODS
OF CONSTANT BENDING STRESS AND ENERGY

The penetration depth P obtained by a penetrator of length L can be defined by the simple equation

$$P = \left(\frac{P}{L} \right) \cdot L .$$

(3)

Here L means the length of the penetrator as already defined in equation (2) and $\left(\frac{P}{L} \right)$ stands for the well-known experimentally defined S-shaped curve showing the efficiency of rod penetrators as a function of striking velocity and aspect ratio, so that

$$\left(P\!\!\Big/_{\!\!L}\right) = \left(P\!\!\Big/_{\!\!L}\right)_{\exp} = f(v, L\!\!\Big/_{\!\!D}) \ .$$

If the aspect ratios of the cylinders are relatively high (say L/D>30), then the dependency of the efficiency values on the aspect ratio is not very significant any longer. Then we can write:

$$\left(P\!\!\Big/_{\!\!L}\right) = \left(P\!\!\Big/_{\!\!L}\right)_{\exp} = f(v) \ .$$

(4)

Equations (3), (2) and (4) lead to

$$P = f_E^{\frac{1}{5}} \cdot \left(\frac{L^2/D}{v}\right)^{\frac{2}{5}} \cdot \left(P\!\!\Big/_{\!\!L}\right)_{\exp}.$$

(5)

In order to find the maximum value of P we follow the procedure described by Frank and Zook in 1987 [10].

The optimum of P vs. v is found from $dP/dv = 0$. Without going into detail, we deduce from equation (5) the following condition for our special case:

$$\frac{2}{5} \cdot \frac{(P/L)}{v} = \frac{d(P/L)}{dv} \ .$$

(6)

Thus it is evident that the optimal velocity v for the maximum value of P is found in the diagram P/L vs. v at that value of v where the gradient of the efficiency curve is equal to the slope of the line drawn from the coordinate centre to the point with the coordinates $\{ v; (2/5) \cdot (P/L) \}$ (see also figure 11).

As a result the following figure 10 shows the interdependence described above in a single graph as a function of velocity v. As far as possible the functions in the figure follow the same order as in the legend. The efficiency curve P/L (medium solid line) shown here is deduced from experiments with long-rods with aspect ratios of about 40. Then, evaluated from equation (5) by means of the P/L-curve, there is the solid line representing the penetration depth P of a long-rod of constant energy and bending stress. The maximal value of this penetration curve is then found according to the optimum condition of equation (6). The construction of the maximum is also depicted in the graph with essential points marked by squares: the optimum of the P-curve is found at that very value of v where the tangent to the P/L-curve (thin line) is parallel to the straight (dashed) line with the slope $(2/5) \cdot (P/L)/v$. Furthermore, the circles show the data of the reference projectile for comparison with the optimum value found here.
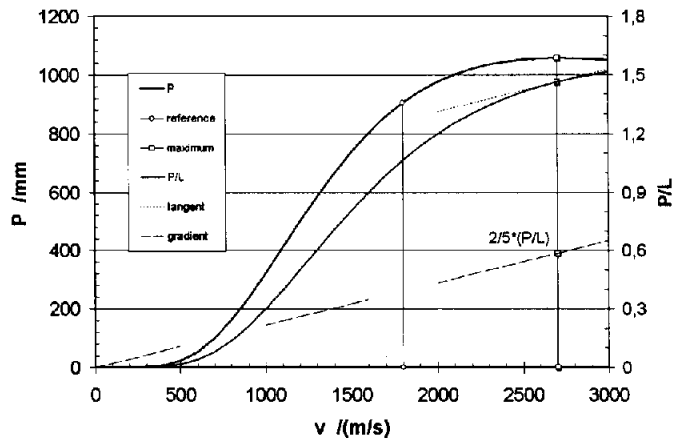

Fig. 10. Energy-efficient penetration for rods of constant bending stress and energy.

Table 1. Comparison between reference and optimized long-rod penetrator

(name)	D	L	L/D	m	v	P
(unit)	mm	mm	1	g	m/s	mm
reference	25	850	34	7300	1800	904
optimum	18	723	40	3250	2700	1058

Table 1 gives some data for a comparison between the reference projectile and the optimized long-rod penetrator. The penetration depth of the optimized penetrator is found to be 1058 mm at a striking velocity of 2700 m/s. Both efficiency and velocity are much higher than in the case of the reference projectile, the data of which are 904 mm at 1800 m/s. Because of the constant energy condition we only get less than 50% penetrator mass at optimum velocity. Compared to the reference penetrator, the optimization procedure results in a rod of both smaller length and diameter, but yet higher aspect ratio, thereby increasing by nearly 1/5 the penetration power of the energy-efficient penetrator at constant bending stress.

OPTIMAL PENETRATION EFFICIENCY FOR RODS OF CONSTANT ENERGY: COMPARISON BETWEEN RODS OF CONSTANT BENDING STRESS AND CONSTANT ASPECT RATIO

As already mentioned, an optimization of the penetrator efficiency at constant energy is usually performed for rods of constant aspect ratio. This procedure was first proposed by Frank and Zook [10] and has experienced further interpretation by Hohler and Stilp [11] and Wollmann and Weihrauch [12, 13].

Now it is interesting to compare the two methods of projectile design, especially as far as the results of the optimization in terms of penetration depths are concerned. As shown by Frank and Zook, the condition for the maximum value of penetration depth in the case of rods with L/D=const. is

$$\frac{2}{3} \cdot \frac{(P/L)}{v} = \frac{d(P/L)}{dv} .$$

(7)

Remarkably, the two equations (6) and (7) only differ concerning the numerical factor. Then of course, the optimum can be found in the same manner as already described, i.e. the optimal velocity v for the maximum value of P is found in the diagram P/L vs. v at that value of v where the gradient of the efficiency curve is equal to the slope of the line drawn from the coordinate centre to the point with the coordinates { $v; (2/3) \cdot (P/L)$ }.

For evaluation figure 11 shows the diagram efficiency vs. velocity, as taken for rods of high aspect ratio. You can also observe the constructions for the optimum striking velocity with slope and tangent for penetrators of constant aspect ratio (dashed lines) and constant bending stress (solid lines). From this it is evident that penetrators following the two construction parameters f_L and λ necessarily have differing optimum velocities. Furthermore, according to the S-shaped efficiency curve it is also apparent that the optimal velocity for constant-stress rods will
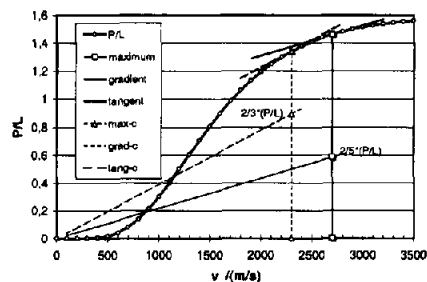

Fig. 11. Construction: optimum striking velocity (slope, tangent) at constant energy for penetrators of constant aspect ratio (dashed) and constant bending stress (solid), respectively.

Table 2. Comparison between energy-optimized penetrators
of constant aspect ratio and constant bending stress

penetrator type	(name)	v	m	D	L	f_L	L/D	P
	(unit)	m/s	g	mm	mm	m	1	mm
both	reference	1800	7300	25.00	850	28.90	34.0	904
λ=const.	opt. λ	2300	4470	21.23	722	24.54	34.0	970
f_L=const.				20.54	771	28.90	37.5	1035
λ=const.		2700	3250	19.08	649	22.05	34.0	949
f_L=const.	opt. f_L			18.07	723	28.90	39.9	1058

be higher than for rods of constant aspect ratio, the corresponding values of which are 2700 m/s and 2300 m/s, respectively.

The following figure 12 shows a direct comparison of the penetration power for the two cases under consideration. At the reference velocity of 1800 m/s we have identical penetrators (D=35 mm, L=850 mm, λ=34, f_L=28.9) with a penetration power of 904 mm (compare with Table 2).

The optimum penetration for the λ-type penetrators is reached at 2300 m/s with a maximum value of 970 mm, i.e. there is only a further increase of some 7%. The value of f_L decreases from 28.90 to 24.54 which is synonymous with a stress decrease of 15% (compare with equation (1)). At this impact velocity (2300 m/s) the f_L-type rod reaches a penetration of 1035 mm corresponding to an increase of about 15%. This value is even nearly 7% higher than the optimum of the λ=const.-penetrator.

The optimal efficiency of the f_L-type penetrator is found at

Fig. 12. Energy-efficient penetration for rods of constant aspect ratio (dashed, index c) and constant bending stress (solid line).

an impact velocity of 2700 m/s, showing a maximum penetration of 1058 mm. There the rod has a diameter of 18 mm and a length of 723 mm, resulting in an aspect ratio of 40. Compared to the reference penetrator the penetration depth could be increased by 17% (and still by 9% compared to the optimum of the λ-type penetrator with L/D=34).

Although there was a decrease of 15% in rod length and of 55% in rod mass it must be noticed that thanks to the method of constant bending stress introduced here the penetration performance could be increased remarkably.
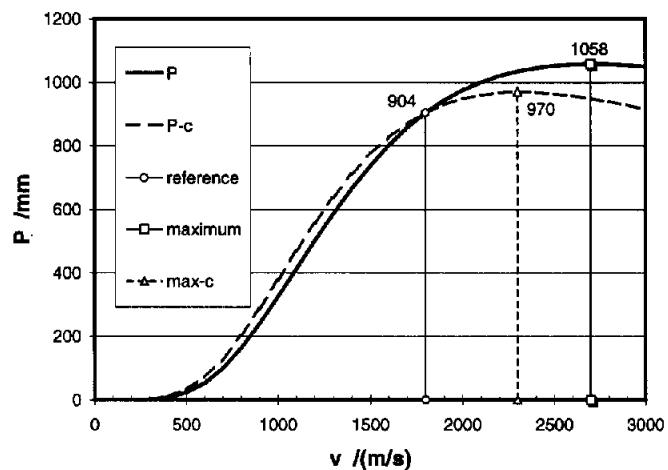
FINAL REMARKS

Our studies concerning the penetration performance of long-rod penetrators and their interaction with modern targets have shown the possibility of optimizing a long-rod penetrator while taking into account the lateral forces exercised for instance by moving target elements.

Hence, a method was established for designing long-rod penetrators being characterized by constant values of bending stress and deflection if subjected to lateral accelerations. Typically this does not result in rods of constant aspect ratios. Then, considering rods of equal energy, these penetrators were examined for maximum penetration efficiency.

This was performed by using the optimization procedure of the energy-efficient penetration with penetrators of constant energy and constant stress level. This procedure resulted in an optimal velocity of 2700 m/s. In comparison to the reference penetrator (L/D=34, v=1800 m/s) the optimum penetrator has of course a reduced mass, but also a reduced length and diameter showing an aspect ratio of 40. The perforation power could be increased by an amount of 17%.

As could be shown, the optimization procedure of the energy-efficient penetration leads to an optimal velocity well in the hypervelocity regime. The respective value for projectiles of equal stress level is significantly higher than for penetrators of equal aspect ratios. Furthermore, the penetration efficiency could also be increased. Therefore, it is evident that the gain in penetration power is due to the special design of the penetrators with a constant level of bending stress, thereby making full use of the material strength. Thus the design method under discussion could probably be an advantageous tool for the optimization of long-rod penetrators with regard to structural integrity and lateral forces.

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