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WHIPPLE SHIELDS AGAINST SHAPED CHARGE JETS

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The known Whipple shield principle has been extended to defeat shaped charge jets. The jet penetration is brought to multiple unsteady interactions with thin shields instead of conventional steady penetration into homogeneous targets. Experiments were performed with targets comprising multiple 0.2–0.5 mm thick spaced metal shields. Principal regularities of the interaction of shaped charge jets with the shields have been established. Multiple shields were found to provide mass saving by factor of 5–7 relative to homogeneous steel of the same performance, at the penalty of two-fold increase in thickness. Implications of the work should be considered as a starting point for further investigations.

INTRODUCTION

According to the generally accepted theory of penetration by shaped charge jets based upon the steady flow model [1], the jet length, L, engaged in cratering and the crater depth, P, are related as $L/P = (\rho_T/\rho_J)^{1/2}$, where ρ_T and ρ_J are the target and jet densities, respectively. This implies that a definite mass of the target material must be involved in penetration for the jet to be consumed in cratering. It is characterized by areal density of the target $M = P\rho_T$.

On the other hand, hypervelocity unsteady interaction of compact bodies with thin targets results in a considerable deformation and disintegration of the striking body after piercing the target, i.e. without contacting it. This phenomenon is widely used to protect spacecrafts from meteorite and debris threat (Whipple shield bumpers) [2]. It must be emphasized that the role of protecting shields is reduced to generation of a shock wave in the striking body. Its fracture and deformation (shortening) is due to release of the shock loaded body and is caused by tensile stresses exceeding strength of its material [3, 4].

An extension of the above principle for defeating shaped charge jets seems to be a problem of both physical interest and practical importance. The problem can be stated as follows: Substitution of multiple unsteady interactions of a shaped charge jet with thin shields for the steady penetration. Then an increase in the jet shortening would be expected without increasing the target density or, what is more, by decreasing it.

It was the aim of the present work to check experimentally that prediction and study principal regularities of the interaction of shaped charge jets with multiple shields.

MODEL EXPERIMENTS

Shortening of elongated projectiles after piercing a shield was checked in model experiments with lead projectiles and targets at impact velocities of about 650 m/s. Under these impact conditions, stresses induced in the lead projectile are far above its yield strength, and a flow of the projectile occurs after piercing the shield. Experiments of this sort simulate qualitatively behavior of a copper impactor at velocities characteristic of shaped charge jets.

Configurations of the modeling experiments and their results are clearly seen in Figs. 1 and 2. The high-frequency photograph in Fig.1 shows the projectile to be shortened by 2.8 mm after interaction with the 0.25 mm thick shield. Data presented in Fig. 2 indicate that the penetration of the projectile into a witness target is the same after piercing a 10 mm thick lead plate and five 0.8 mm thick lead shields. It is readily seen that the unsteady interactions are much more effective with regard to the projectile shortening than the steady penetration.

The above experiments evidence unambiguously that spaced thin shields can provide a drastic mass saving of a protection that cannot be conceptually achieved in protecting structures penetrated in the steady-flow mode.

EXPERIMENTS WITH SHAPED CHARGE JETS

Performing experiments

The experiments were carried out with 25 mm diameter shaped charges of flegmatized RDX having 60° cone copper liners. The charges were fired at a standoff distance of

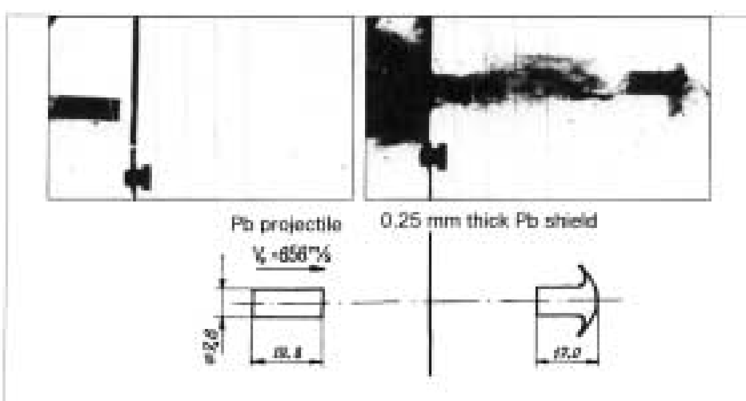

Figure 1. Piercing a 0.25 mm thick Pb shield by a Pb projectile.

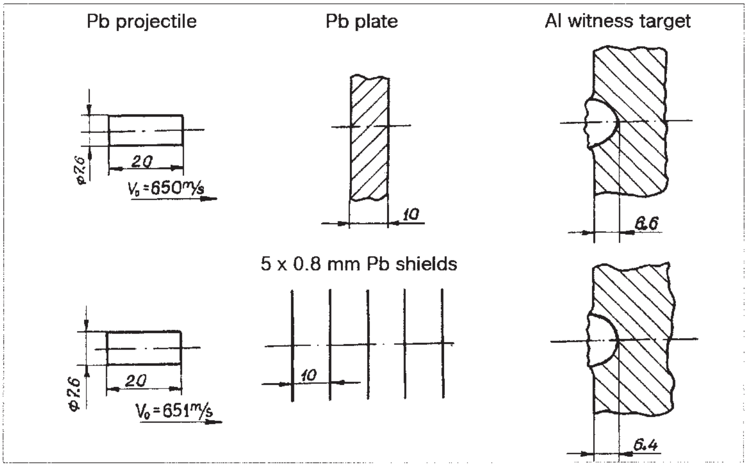

Figure 2. Comparing performance of a Pb plate and multiple Pb shields.

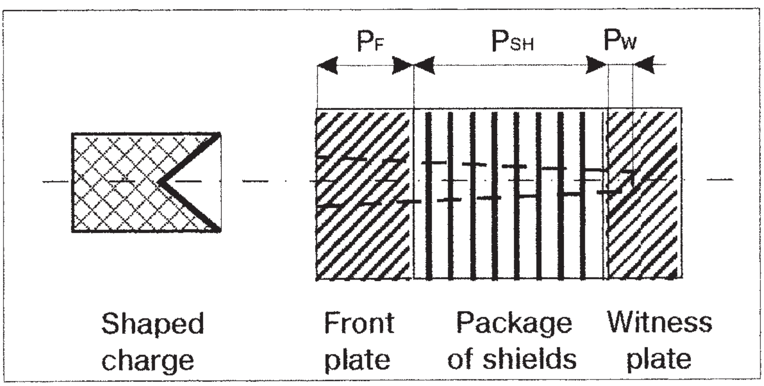

Figure 3. Test configuration for shaped charge jets.

30 mm. Under these conditions, mean depth of penetration into a reference steel target (hardness of 2 GPa), P_{REF} = 82.5 mm, spread of the depth being within 2.5%.

Configuration of the test target is schematically shown in Fig. 3. A steel front plate of varied thickness was followed by a package of spaced shields and steel backing plate which served as a witness target. The package is characterized by number of shields, n, single shield thickness, T, and spacing between the shields, δ.

From experimental data, a thickness of steel, P_{EQ}, was found equivalent in the jet shortening to the shield package: $P_{EQ} = P_{REF} - (P_F + P_W)$, and its areal density: $M_{EQ} = P_{EQ}\rho_{REF}$. With a known thickness of shield package, $P_{SH} = n(T + \delta)$, and its areal density, $M_{SH} = P_{SH}nT$, differential space efficiency, $Es = P_{EQ}/P_{SH}$, and mass efficiency, $E_M = M_{EQ}/M_{SH}$, were calculated for the shield package. From P_{EQ}, the ratio P_{EQ}/n was calculated characterizing thickness of a stratum of the homogeneous reference steel target having the same performance as a single shield. This ratio is of importance when dealing with packages comprising various number of shields.

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The values of P_{EQ} were also derived by comparing penetration versus time curves for reference and test targets obtained using conventional shorting gage technique [5].

An effect of shield properties

In the first set of experiments, performance of shields was studied depending on their density and thickness. These properties determine stress level and length of the shock loaded zone in the jet, i.e. initial conditions for rarefaction of the shocked jet causing its deformation.

The shock pressure on the jet-shield interface can be expressed within the acoustic approximation as $\rho_J C_J U_J = \rho_{SH} C_{SH} U_{SH}$ [3], where p, C, and U are density, sound velocity, and particle velocity, respectively. The shield thickness, T, determines duration of the pressure pulse and, hence, length of the shock loaded zone in the jet, which depends also on the striking body diameter.

Experimental data are presented in the Table.

Efficiency of the shields depending on their density and thickness

Shield material	Steel	Al	Al	Steel mesh*)
Single shield thickness, T (mm)	0.5	0.5	0.2	0.55
Number of shields, n	50	50	50	30
Spacing, δ (mm)	1.0	1.0	1.0	1.0
Thickness of equivalent steel, P_{EQ} (mm)	35	35	25	23.3
Differential space efficiency, P_{EQ}/P_{SH}	0.47	0.47	0.42	0.51
Differential mass efficiency, M_{EQ}/M_{SH}	1.4	4.04	7.2	4.8

*) $\rho_{SH} = 2.3$ g/cc

It follows from the data that the density of shields under study has no effect on their performance. This result looks paradoxically in terms of the steady-flow penetration model. However, it is quite reasonable with respect to shock loading and rarefaction phenomena. At impact velocities of 3–4 km/s, shock pressure in the jet is 60–70 GPa when impacting steel shields and 45–50 GPa when impacting Al shields. These pressures give rise to tensile stresses under release exceeding yield strength of the jet material by about two orders of magnitude. Thus, the shield density does not markedly affect the deformation of the jet caused by rarefaction outside the shield.

When considering the shield thickness effect, it is seen that the package of 50 x 0.5 mm Al shields is equivalent to 35 mm steel penetrated in the steady regime, and the 50 x 0.2 mm package is equivalent to 25 mm steel. It is reasonable to assume that the higher performance of 0.5 mm shields is due to a longer duration of the shock pressure pulse generated in the jet. Then a greater part of the jet can flow after release outside the shield. On the other hand, the package of 0.2 mm shield has a higher mass efficiency, EM, despite the package of 0.5 mm shields provides a greater jet shortening. This can be attributed to the length of the shock loaded zone in the jet, which is known to be restricted due to rarefaction waves propagating from free side surfaces of the jet [4]. This means that an increase in duration of the pressure pulse exceeding a definite value cannot lead to a further increase in length of the shock loaded zone. From this point of view, there are strong reasons to believe that the shield thickness of 0.5 mm exceeds an optimum value under conditions of the experiments performed.

Determining optimal shield thickness needs further investigations. This problem should be solved with due regard for the jet diameter.

Noteworthy is the found high performance of mesh shields. This can offer a higher differential mass efficiency as against that of plate shields. This finding is in line with data [6, 7].

An effect of the shield package design

Taking into account the above discussed data, regularities of the behavior of shield packages were studied in experiments with mesh shields. Brass mesh shields were used having thickness of 0.25 mm (wire diameter of 0.12 mm, 0.2 x 0.2 mm mesh, density P_{SH}= 2.25 g/cc).

The work was focused on studying effects of spacing between the shields, number of shields, and location of the package in a combined target on performance of the shield package.

Spacing between the shields determines a distance for a “free flight” of the jet, at which the jet shortening is allowed without contacting a shield. Data on variation of the package performance with number of shields enable to find out whether the shields work additively, i.e. independently of each other. Location of the shield package in a target is of importance because of a velocity gradient along the jet causing the jet elongation and particulation. Thus, the shield package interacts with either continuous or particulated jet depending on location of the package in the target.

The experiments were performed with targets as shown in Fig. 3. The total shield package thickness of 30 mm was the same in all the shots. The front steel plates were 10 mm and 40 mm thick. In the first case (10 mm), the shields interacted with a continuous, progressively stretching jet. After piercing the 40 mm front plate, the jet was found to be particulated, and its cumulative length remained constant.

Experimental data are presented in Figs. 4–6. Fig. 4 shows the variation of differential mass efficiency, E_M, with the spacing between the shields, δ, normalized to the shield thickness, T.

Curves 1 and 2 are for particulated and continuous jets, respectively, the dashed line represents calculation in terms of the steady hydrodynamic penetration for a medium of the shield density, ρ_{SH}. The run of curve 1 evidences that E_M increases with δ/T from zero up to two and remains constant with further increase in δ/T. It follows that the jet shortening terminates within a distance of about two shield thicknesses. The optimal spacing of δ/T = 2 is supported by the fact that maximum differential space efficiency of the shield package was observed at δ/T = 2 (see Fig. 5). Noteworthy is the fact that experimental points for zero spacing (δ/T = 0) coincide with the hydrodynamic calculation. This means that tightly contacting shields interact with the jet by the common steady-flow mechanism.

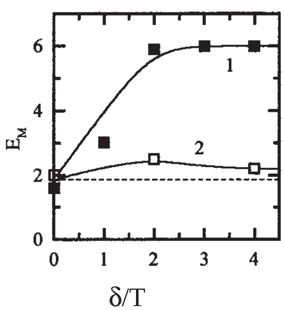

Figure 4
Differential mass efficiency of the shield package versus normalized spacing.

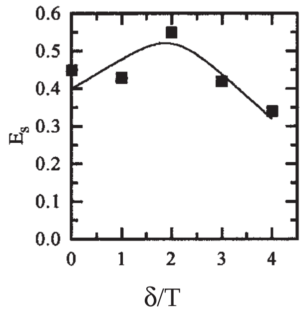

Figure 5
Differential space efficiency of the shield package versus normalized spacing.

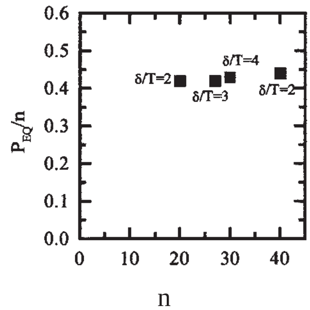

Figure 6
Performance of the single shield versus number of shields in the package.

Comparing curves 1 and 2 in Fig. 4 shows a markedly lower efficiency of shields interacting with the continuous jet. It can be related to the fact that a continuous jet moving in the gap between the shields is being elongated as affected by the velocity gradient. This makes up for the jet shortening due to the interaction with the shield.

Thus the best performance of a shield package can be attained in interacting with completely stretched jets. It is this condition that determines the optimal location of a shield package in combined targets.

Performance of shields in packages comprising various number of shields can be followed in Fig. 6. It shows thickness of the stratum of a homogeneous steel target equivalent to the single shield, P_{EQ}/n, versus number of shields in the package, n. The data are presented for normalized spacings $\delta/T \geq 2$ at which maximum efficiency is attained. It can be seen that P_{EQ}/n remains close to a constant value. This leads to the conclusion that the shields in package work independently of each other and additively.

CONCLUSIONS

The principal conclusion derived from the present study is that succeeding unsteady interactions of a shaped charge jet with multiple spaced shields result in a much greater jet shortening per unit mass of the penetrated target as compared with the steady penetration. Differential mass efficiency of a system of spaced shields is as great as 5–7 relative to steel and cannot be shared by conventional “passive” protecting structures. However, the mass saving is attained at the penalty of deterioration of space efficiency (down to about 0.5).

Statement of the present work was based upon implications of long-standing extensive investigations of Whipple shields defeating compact bodies at hypervelocities. Studying unsteady interactions of shaped charge jets with multiple shields is a relatively young area of penetration mechanics. Nevertheless, the results obtained show an extension of the Whipple shield principle to shaped charge jets to hold much promise for mass saving of protecting structures.

The authors realize that the present work should be considered as a starting point for further investigations aimed, first of all, at a better understanding of the mechanism of unsteady interaction of shaped charge jets with shields as well as at practical applications of the suggested principle.

REFERENCES

1. G. Birkhoff, D. McDougal, E. Pugh, G. Taylor, "Explosve with lined cavities", *J. Appl. Phys.* 19 (6), 563–582, 1948
2. B. Cour-Palais, J. Crews, "A Multi-Shock Concept for Spacecraft Shielding", *Int. J. Impact Engng.* 10, 135–146, 1990
3. Yu.B. Zeldovitch, Yu.P. Raiser, "Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena", Academic Press, N.Y., 1967
4. N.A. Zlatin, in: "Ballistic Apparatus and Their Applications to Experimental Research" (Ed. by N.A. Zlatin and G.I. Mishin), Nauka, Moscow, 1974 (in Russian)
5. M. Held, "Evaluation of Shaped Charge Penetration Efficiency by Advanced Diagnostic Technique", *Proc. 6th Intern. Symp. on Ballistics,* 480–493, 1981.
6. F. Hortz, M. Cintala, R Bernhard, "Multiple Mesh Bumpers: a Feasibility Study", *Int. J. Impact Engng.* 17 (1–6), 431–442, 1995
7. G. Belov, E. Dyakin, S. Protasov, A. Petrushin, G. Smirnov, "Penetration of Compact Steel Projectiles into Heterogeneous Metal Target of TWF Type ", *Int. J. Impact Engng.* 23 (1), 63–66, 1999