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STRESS WAVES IN BOUNDED MEDIA

Quarterly Report
September 1, 1965 to November 30, 1965

BUREAU OF MINES, PITTSBURGH, PA.

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DEPARTMENT OF
THE INTERIOR

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Prepared for:

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by

Richard W. Watson
Karl R. Becker
Frank C. Gibson

Approved:

Robert W. Van Dolah
Research Director
Explosives Research Center

U. S. Department of the Interior
Bureau of Mines
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STRESS WAVES IN BOUNDED MEDIA

Introduction

The program to determine the factors affecting the energy transferred from detonating explosives to coupled metal plates has been continued. The variables under consideration include the properties of the explosive as well as the choice of the materials in the explosive-plate combination. The latter involves the shock impedance match between the explosive and metal plate, as well as the effects of charge geometry and the degree of coupling between the explosive and the plate. During the quarter, an effort was made to improve the precision of the observations over that of the preliminary results presented in a previous report[1/]. In addition, several groups of firings have been completed during the past quarter using five explosives in combination with four different plate materials. The results of these tests will be discussed in this report.

Experimental Techniques

With the exception of a few tests dealing with edge effects, the data to be presented were derived from experiments carried out with the experimental arrangement shown in figure 1. It consists of a metal plate 6 inches long and 3 inches wide, having a thickness t_p, depending upon the nature of the tests. The plate was coupled to a 6-inch long x 3-inch wide x 1-inch thick explosive charge; the charge was initiated by a

1/ Watson, R. W., K. R. Becker, and F. C. Gibson. Stress Waves in Bounded Media. Bureau of Mines Quarterly Report, U. S. Army Ordnance, Aberdeen Proving Ground, Md., June 1, 1965 to August 31, 1965.

1-1/2-inch long tapered section of the same explosive, together with a 1-inch long x 1-inch diameter tetryl booster. Flash radiographs were then taken during detonation of the charges to determine the maximum departure angle of the plate, ϕ, with respect to the charge axis. Values of ϕ coupled with previous measurements of the detonation rate, U_D, are used to compute the normal component of plate velocity, $V_n = U_D \sin \phi$ from which the energy transfer is assessed. For the experiments to be considered, the normal plate velocity is within one percent of the true material velocity given by the Taylor relationship, $V = U_D \sin \frac{\phi}{2}$ 2/. This is well within the experimental error in the measurement of ϕ which is estimated to be about two or three percent. Experiments were conducted with five different explosives--Composition B (Comp B), trinitrotoluene (TNT), 50/50 nitroglycerin-ethylene glycol dinitrate (NG-EGDN), pentolite, and nitromethane (NM). These were used in combination with four metals: lead (ρ = 11.35 g/cm^3), copper (ρ = 8.89 g/cm^3), aluminum (ρ = 2.78 g/cm^3), and magnesium (ρ = 1.74 g/cm^3). These explosive-metal combinations were chosen as representing a reasonably wide range in the variables considered pertinent to the energy transfer process.

To date, four groups of firings have been completed that were designed to explore: (1) edge effects; (2) the relative energetics of the five different explosives; (3) the role of impedance match between the explosive and the metal; and (4) the effects of decoupling the explosive and metal.

2/ Birkhoff, G., D. P. MacDougall, E. M. Pugh, and Sir Geoffrey Taylor. Explosives with Lined Cavities. Journal of Applied Physics, Vol. 19, No. 6, 563-582, June 1948.

Experimental Results

Edge Effects

Some of the preliminary results reported in the last progress report indicated that the energy transfer was being affected by early rarefactions from the edges of the explosive charge[3/]. In order to eliminate this complication and further to minimize explosive weight requirements, a series of tests was carried out with charges of constant thickness but varying widths. One-inch thick x 6-inch long slabs of Comp B having widths of 2, 3, and 4 inches were used; they were coupled to 1/8-inch thick copper plates having the same width as the explosive slab and a length of 6 inches.

The results of this series of tests are presented in table 1 in terms of the observed departure angle, Ø, and the calculated value of normal plate velocity, V_n. Comparison data from previous firings conducted with 1-inch thick x 2-inch wide Comp B charges coupled to 1-inch wide x 1/8-inch thick copper plates are also presented. It will be noted that there appears to be a small but significant increase in plate velocity when the charge-plate width is varied from 2 to 3 inches. In addition, the 2-inch wide charge-plate combination yielded a somewhat higher plate velocity than did the 2-inch wide charge coupled with a 1-inch wide plate. There was no increase in velocity when the charge width was increased beyond 3 inches; in order to keep the charge size practical, a width of 3 inches was chosen for the remainder of the experiments.

3/ See work cited in reference 1.

Relative Energetics of Several Different Explosives

In order to classify the several explosives used in this program according to their ability to accelerate metal plates, experiments were carried out with two separate charge arrangements. The first consisted of a 1-inch thick explosive charge directly coupled to a 1/8-inch thick copper plate. Since the density of the explosives varied from 1.14 g/cm^3 for NM to 1.72 g/cm^3 for Comp B, this represents a case of variable charge-mass/plate-mass ratio, C/M. A 1-inch thick explosive slab was also used for the second arrangement but the thickness of the copper plate was varied for each explosive to produce the same ratio of C/M. Plate velocity data, from which the plate kinetic energies were calculated, are presented in tables 2 and 3, while table 4 compares the explosives on the basis of $\frac{E_p}{m_x}$, the delivered kinetic energy per unit explosive mass.

Several aspects of results summarized in table 4 are worthy of note. The variable C/M charge design yielded values of $\frac{E_p}{m_x}$ ranging from 467 joules/g for NM in the variable C/M geometry to 816 joules/g for NG-EGDN in the constant C/M trials. Thus, the charge geometry used here represents an extremely inefficient mode of energy coupling between the explosive and plate. Some recent results from the work of a group at Livermore[4/] afford some interesting comparisons on this point. For internally loaded 0.1-inch wall x 1.0-inch

4/ Kury, J. W., H. C. Hornig, and E. L. Lee. Metal Acceleration by Chemical Explosives, Lawrence Radiation Laboratory, Livermore, California. Presented at the Fourth Symposium on Detonation, U. S. Naval Ordnance Laboratory, White Oak, Silver Spring, Md., Oct. 12-15, 1965.

id copper cylinders they report terminal casing velocities of 1.63, 1.40, and 1.22 mm/μsec for Comp B, TNT, and NM respectively. Using the simple Gurney approach, the available explosive energy $\left(E = \frac{V_o^2}{2R}\right.$, where V_o = terminal casing velocity and $\left.R = \frac{C/M}{1 + 1/2\ C/M}\right)$ is thus calculated to be 3684 joules/g for Comp B, 2882 joules/g for TNT, and 2940 joules/g for NM. Using these values as the total av.ilable energy, the efficiency of coupling in the slab charges with variable C/M is computed to be 19.5 percent, 17.0 percent, and 15.9 percent for Comp B, TNT, and NM, respectively. The corresponding values for the charge design having constant C/M are 19.5 percent, 18.9 percent, and 19.6 percent. These low values of coupling efficiency are associated with the presence of an unconfined explosive surface which allows for the free escape of the detonation products. The pronounced effect of charge geometry on the efficiency of coupling between the explosive and metal further illustrated by the fact that the experiments reported in reference 4 yield values of $\frac{E_p}{m_x}$ of 3044, 2365, and 2561 joules/g for Comp B, TNT, and NM, respectively. These values are between 4 and 5 times larger than those observed in the slab geometry.

Since the transfer efficiency values given for the Comp B, TNT, and NM charges of constant C/M are reasonably constant themselves, it is of further interest to use the average value of 19.3 percent to estimate the available energy of NG-EGDN and pentolite, two explosives used in our program but not treated in reference 4. Using this value and the values of

816 joules/g and 814 joules/g derived from the slab firings the values of the available energy, E, are calculated to be 4227 joules/g for NG-EGDN and 4217 joules/g for pentolite. These values are about 15 percent in excess of the value of 3684 joules/g computed for Comp B. It appears desirable to derive a corresponding set of available energy values for these two explosives from data obtained in the cylindrical geometry; experiments have been designed for this purpose and are currently underway.

Another feature of the results of these experiments that bears further discussion is the fact that the coupling efficiency appears to be an increasing function of C/M over the range of C/M values used here. This could be interpreted as implying that the value of C/M for maximum efficiency is above the largest value of 1.548 used in these firings. A complete mapping of the functional relationship between V_n and C/M would be required to clarify this point. It is anticipated that such data on one or several of the explosives used in this program will be available in the near future.

Effects of Plate Material

The third series of experiments, carried out with the charge geometry of figure 1, was designed to determine the degree to which explosive energy transfer was affected by the shock impedance match between the explosive and the metal plate. For this purpose, experiments were conducted with magnesium, aluminum, copper, and lead plates coupled to 1-inch thick charges of Comp B and NG-EGDN. The copper plates were 0.125 inch thick for Comp B and 0.113 inch thick for NG-EGDN, giving a value of C/M equal to 1.548. The thicknesses of the other plate materials were adjusted to yield a constant C/M.

The four metals employed in this experiment represent a considerable range in shock impedance match (mismatch) between the explosive and the metal which results in a broad range of peak shock strengths delivered to the plates. For example, a directly incident detonation in Comp B having a C-J pressure of 290 kilobars induces shock pressures of 356 kilobars and 282 kilobars for aluminum and magnesium, respectively, while the induced pressures in copper and lead may be expected to exceed 450 kilobars. For tangential incidence as characterized by the slab geometry, the peak-induced pressures are approximately one-half the above values; thus, if shock effects are important in this particular application they should be discernible in these experiments.

The results of this series of firings are presented in table 5 in terms of the experimental values of ϕ and the calculated values of the normal component of plate velocity V_n. The most significant feature of the results in table 5 is the fact that the values of V_n are nearly independent of plate material. For Comp B the values range from 1.43 mm/μsec for a magnesium plate to 1.5 mm/μsec for a lead plate. This represents a 5 percent difference in velocity with a corresponding difference of 10 percent in energy transfer. For NG-EGDN the maximum spread in velocities again occurred with magnesium and lead plates. In this case the percentage difference in plate velocity and energy transfer was 9 and 18 percent, respectively. While the differences in the observed velocities for the various plate materials are small, they do appear to be significant inasmuch as essentially the same ordering is observed with both Comp B and NG-EGDN. The important conclusion here is that the energy transfer is approximately the same for all four plate materials with the high density materials (high shock impedance) affording only a slightly higher energy transfer.

Interfacial Conditions

A series of experiments was made to determine the effect of decoupling on the total energy transfer to a metal plate in proximity to the detonating explosive. The basic charge geometry of figure 1 was again used but an air gap, ranging from zero to 0.106 inch, was introduced between the explosive and plate by means of spacers at both ends of the assembly. Tests were carried out using 1-inch thick Comp B charges and 1/8-inch thick copper plates. The results of five such firings are presented in table 6; they show no discernible difference in the value of V_n for gaps up to 0.040 inch. For a gap of 0.106 inch there appears to be a slight reduction in the value of V_n from 1.50 mm/μsec averaged over air gaps up to 0.040 inch to 1.44 mm/μsec for the 0.106 inch gap. The corresponding reduction in energy transfer amounts to approximately 8 percent. Thus, in this geometry the results indicate that for charges having relatively high values of C/M of the order of one or more, there is no necessity for intimate contact between the explosive and metal in order to transfer maximum energy. This fact may be of some importance in the design of explosive-metal devices where extremely strong shocks in adjacent metal components cannot be tolerated.

In an effort to estimate the reduction in the shock wave amplitude delivered to the metal in these tests, two additional firings were conducted with a resistive pressure gage placed on the free surface of the copper plates. In one firing, a zero gap was used and the records indicated a delivered pressure of 25.5 kilobars (to the polyethylene gage mount) which corresponds to a pressure of 180 kilobars at the copper free surface. The second firing which was made with a 0.106-inch gap gave a 17.0-kilobar delivered pressure with a corresponding pressure in the copper of 127 kilobars. Since the gage was calibrated for a normally incident wave, the values quoted here are not precise; they do however illustrate that small air gaps, while not affecting plate velocity, do result in a marked decrease in the amplitude of the shock wave delivered to the metal.

Conclusions

Important conclusions resulting from this work can be summarized as follows:

(1) The unconfined slab geometry used in these experiments represents a poor mode of energy coupling between the explosives and the metal plates. The kinetic energy transferred to the plate is estimated to be 20 percent of the available explosive energy for C/M values near 1.5. It is anticipated that the efficiency of transfer would improve slightly for somewhat larger values of C/M; however, it should be noted that the efficiency of energy transfer in the internally loaded cylindrical geometry is 4 to 5 times as great, indicating that a fruitful approach to the problem of improving the efficiency of explosive-metal component devices lies in the selection of more effective geometries.

(2) While the initial phases of plate motion undoubtedly depend on the structure of the shock wave set-up in the metal, the results from the impedance match experiments as well as

the air-gap firings indicate that the total energy transfer is not a sensitive function of the initial shock structure. To a very good approximation, the total energy transferred depends only in the mass loading of the plate and the type of explosive.

(3) The fact that on an energy transfer basis, NG-EGDN compares favorably to Comp B coupled with the fact that. NG-EGDN has a considerably lower minimum diameter for detonation than Comp B indicates that the liquid explosives should serve as a useful tool in investigations involving minimal explosive loads.

TABLE 1. - Summary of data from edge effects experiment

Width of Explosive and Plate (inches)	Departure Angle (Ø)	n	Variation (spread)	V_n (mm/μsec)
1*	10.0°	1	-	1.36
2	10.6°	3	0.1°	1.44
3	11.0°	2	0.1°	1.49
4	11.0°	2	0.0°	1.49

Notes:

Explosive: Comp B, 1-inch thick.

Plate material: copper, 1/8-inch thick.

* denotes previously reported results from 1-inch wide copper plates coupled with a 2-inch wide Comp B explosive slab.

n = number of trials.

V_n = normal component of plate velocity.

TABLE 2. - Results of tests to determine energy transfer using a charge design having variable C/M

Explosive	Departure Angle (ø)	n	Variation (spread)	V_n (mm/μsec)	C/M
Comp B	11.0°	2	0.1°	1.49	1.548
NG-EGDN	10.8°	3	0.7°	1.41	1.395
Pentolite	10.9°	3	0.8°	1.40	1.449
TNT	9.9°	2	0.1°	1.18	1.413
Nitromethane	8.9°	2	0.1°	0.98	1.026

Notes:

Explosive thickness: 1 inch.

Plate material: copper, 1/8-inch thick.

n = number of trials.

V_n = normal component of plate velocity.

C/M = ratio of explosive mass to plate mass.

TABLE 4. - Energy transfer from several explosives in the slab geometry

Explosive	Variable C/M			Constant C/M		
	C/M	$\frac{E_p}{m_x}$ (joules/g)	Energy Transfer Relative to Comp B	C/M	$\frac{E_p}{m_x}$ (joules/g)	Energy Transfer Relative to Comp B
Comp B	1.548	717	1.0	1.548	717	1.0
NG-EGDN	1.395	713	0.99	1.548	816	1.14
Pentolite	1.449	676	0.94	1.548	814	1.13
TNT	1.413	491	0.68	1.548	545	0.76
NM	1.026	467	0.65	1.548	579	0.80

Notes:

C/M = ratio of explosive mass to plate mass.

$\frac{E_p}{m_x}$ = energy transfer per unit explosive mass.

TABLE 3. - Results of tests to determine energy transfer using a charge design of constant C/M

Explosive	Plate Thickness (inches)	Departure Angle (Ø)	n	Variation (spread)	V_n (mm/μsec)
Comp B	0.125	11.0°	2	0.1°	1.49
NG-EGDN	0.113	12.2°	3	0.3°	1.59
Pentolite	0.117	12.4°	3	0.4°	1.59
TNT	0.114	10.9°	2	0.2°	1.30
Nitromethane	0.083	12.3°	3	0.7°	1.34

Notes:

C/M = 1.548.

Explosive thickness: 1 inch.

n = number of trials.

V_n = normal component of plate velocity.

TABLE 6. - Results from experiments dealing with intimacy of contact between explosive and plate

Air Gap (mils)	Departure Angle (Ø)	n	V_n (mm/μsec)
0	11.0°	1	1.49
10	11.0°	1	1.49
23	10.9°	1	1.48
40	11.2°	1	1.52
106	10.6°	1	1.44

Notes:

Explosive: Comp B, 1-inch thick.

Plate: copper, 1/8-inch thick.

n = number of trials.

V_n = normal component of plate velocity.

TABLE 5. - Summary of results from energy coupling experiments with two explosives and four different plate materials

Explosive	Plate Material	Plate Thickness (inches)	Departure Angle (ϕ)	n	Variation (spread)	V_n (mm/μsec)
Comp B	Copper	0.125	11.0°	2	0.1°	1.49
Comp B	Aluminum	0.412	10.6°	2	0.2°	1.45
Comp B	Magnesium	0.639	10.5°	2	0.1°	1.43
Comp B	Lead	0.101	11.1°	2	0.0°	1.51
NG-EGDN	Copper	0.113	12.2°	3	0.3°	1.60
NG-EGDN	Aluminum	0.371	11.4°	2	0.4°	1.49
NG-EGDN	Magnesium	0.575	11.1°	2	0.3°	1.46
NG-EGDN	Lead	0.091	12.3°	2	0.1°	1.60

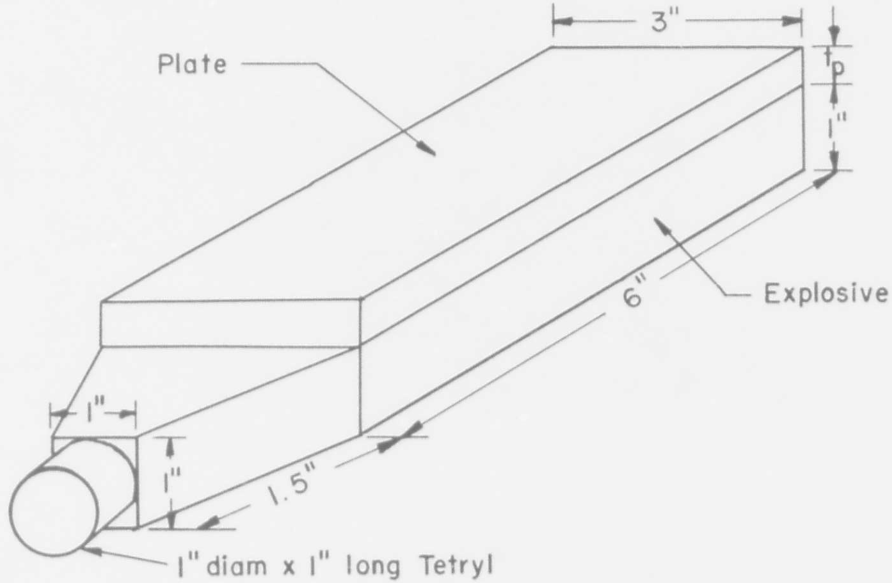
Notes:

Explosive thickness: 1 inch.

n = number of trials.

V_n = normal component of plate velocity.

C/M = 1.548.



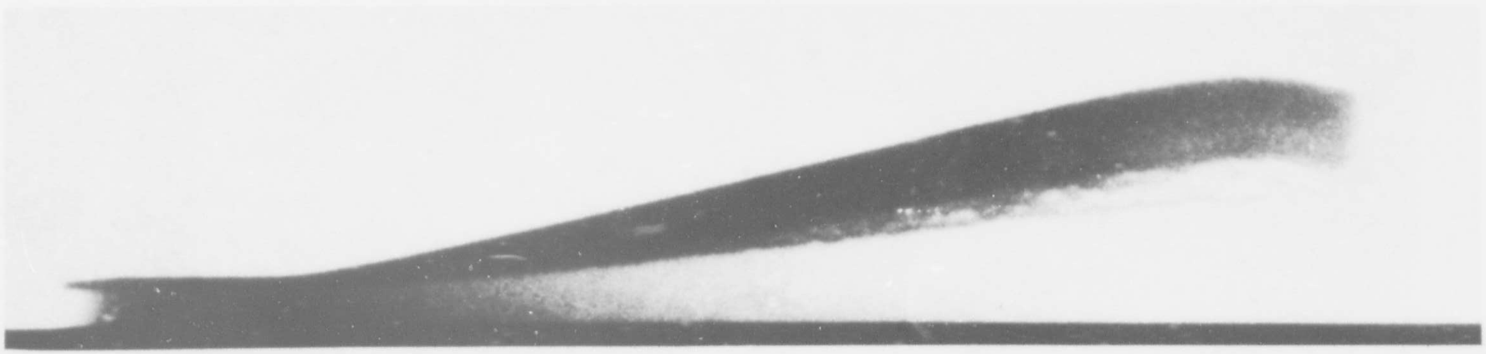


FIGURE 1. - Experimental arrangement used in energy coupling studies together with a typical radiograph used to determine Ø.