ON IMPACT SENSITIVITY AND THE ESTIMATION OF PRESSURES IN EXPLOSION PHENOMENA

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1. Introduction

In experiments on the impact sensitivity of an explosive the latter is generally placed between two hard steel anvils and subjected to the blow of a falling ball, and the probability of explosion determined for different heights of drop. The impact energies required for explosion depend upon the mechanism of initiation. If the explosion is due to the compression of an entrapped gas bubble, the energies of impact are very small as compared to the case when the explosion occurs by the viscous heating of the explosive or by its rubbing against grit particles. There have been some attempts to assess the pressures generated on the explosive layer under the above conditions but there seems to be no straightforward theoretical treatment of the subject. The present note describes such an attempt. It is essentially based on a modification and an extension of our previous publication (Murgai, 1954) embodying an application of the Hertz theory of impact. There we calculated the pressures on the explosive layer by the distribution of the force of impact over the area of cross-section of the upper anvil, the force of impact being determined by regarding the ball and the upper anvil as the two colliding bodies.

It was however realized that in this method of calculation of pressures (i.e. by the distribution of the force of impact over the area of the anvil) the actual mass of the anvil would be of no importance, as it is generally very small, and should be replaced by the mass of the whole assembly, regarded as one single rigid system, for the purpose of calculating the force. Method (1) described here therefore differs from that used in our earlier publication (Murgai, 1954) in this respect. The present note as opposed to the earlier one also takes account of the dependence of elastic constants on the dynamic conditions of loading, though in a general way. In the absence of any precise knowledge of such a dependence we thought of calculating the pressures for two sets of elastic constants—one for steel to steel impact, and the other for steel to a solid having elastic constants one-tenth that of steel—expecting that the experimental pressures would lie between these two calculated values. This was found to be the case for observed pressures, when measured without the explosive under the anvil, but for cases when the explosive is present the experimental pressures were less than both the calculated values. From this it might be inferred that the thin layer of the explosive does not form a part of the rigid system as assumed in method (1) here, and perhaps gets deformed. Experimental observations support this inference. A rather different attempt was therefore made to determine these pressures. That was done by splitting the calculation into two parts as it were—one dealing with the determination of the velocity of projection of the anvil on to the explosive layer, by the standard laws of impact, assuming a certain value of the coefficient of restitution, and the other with the calculation of the pressures developed when the anvil moving with this velocity would strike the explosive below. The two values of the pressures (corresponding to the two sets of elastic constants) thus calculated lie well on either side of the experimental pressures measured along with the explosive layer in between the two anvils. This note gives an account of both these methods of calculation. A reinterpretation of the results leads to the prediction of a mass versus height relation for fifty per cent explosive efficiency.

2. Calculation of the Pressure

In the reference mentioned above (Murgai, 1954) the pressure on the explosive layer has been calculated by the expression,

$$p = \frac{4}{3\pi}\left(\frac{15\pi}{16}\right)^{\frac{3}{5}}\left(\frac{m_1 m_2}{m_1+m_2}\right)^{\frac{3}{5}}(\phi_1+\phi_2)^{-\frac{2}{5}}\frac{r^{\frac{1}{5}}}{A}v^{\frac{6}{5}} \qquad (1)$$

where m_1 and r are the mass and the radius of the ball, v its velocity of approach, m_2 the mass of the upper anvil, A its area of cross-section. This expression for p results from simplifying the equation (2) of Murgai (1954) after substituting for various quantities. Further we have

$$\phi_1+\phi_2 = \frac{2(1-\sigma)^2}{V_c{}^2\rho\pi(1-2\sigma)}$$

σ is the Poissons ratio of the material, ρ its density, V_c the velocity of compression waves in the medium,

$$V_c = \left(\frac{k+\frac{4}{3}\mu}{\rho}\right)^{\frac{1}{2}}$$

k and μ are the volume elasticity and shear modulus respectively. If m_2 in equation (1) represents the mass of the rest of the apparatus which will be quite large as compared to the mass of the ball, the expression for pressure in terms of the height of fall and the weight of the ball is given by

$$p = \frac{4}{3\pi}\left(\frac{15\pi}{16}\right)^{\frac{3}{5}}(\phi_1+\phi_2)^{-\frac{2}{5}}\frac{1}{A}\left(\frac{3}{4\pi\rho}\right)^{\frac{1}{15}}(2g)^{\frac{3}{5}}m_1^{\frac{1}{15}}(m_1h)^{\frac{3}{5}}. \qquad (2)$$

As a means of finding the theoretical pressures the values of m, h and A from certain experiments may be put in the above equation alongwith the two values of $(\phi_1+\phi_2)$ and the results compared with the experimentally observed pressures. The only reliable measurements in this connection are those of Hollies *et al.* (1953) who have determined pressures by measuring times of impact, rebound heights of the falling balls and the coefficient of restitution, in impact sensitivity experiments on initiators. They made these measurements both with and without the explosive underneath the striking pin. They observed that while the rebound heights and hence the coefficient of restitution was sensibly the same with and without the explosive under the hammer, the times of impact were considerably different. In fact these were less by a factor of three to four in the latter case (i.e. without the explosive). This observation would place the pressures generated in their experiments without the explosive about three to four times those when the explosive is there (under the hammer). Substitution of m, h and A from their experiments in equation (2) above gave two values of p which lay on either side of the former than the latter. Another point is worth mentioning here. If in equation (2) we assume a constant value for p—the experimentally determined value for fifty per cent explosion efficiency—the mass versus height relation comes out to be mh=constant—the experimental relation of Taylor and Weale (1932). But since, as mentioned already, the calculated values of p do not agree with measured values for fifty per cent explosion efficiency, the above mass versus height relation has a limited significance. The interest in retaining equation (2) however lies not only in that it gives correct order of pressures under the conditions specified above, but also in the fact that it points out what may likely be happening when the explosive is placed in between the anvil and the striking pin. The fact that in such cases the calculated pressures are higher than the observed ones, leads to the conclusion that the thin explosive layer does not form a rigid part of the rest of the assembly—an assumption which is an essential basis of equation (2). This layer gets perhaps much more deformed than the steel parts above and below this. Resort was therefore made to an alternative approach consisting in regarding the upper anvil as a separate body and finding the pressures developed when it is projected with a certain velocity on to the explosive layer. Before recounting the results, we briefly outline below the derivation of an expression representing the pressures obtained on impact of two flat surfaces.

Impact of Flat Surfaces

Let m_2 and m_3 be the masses of two cylinders, moving with their flat faces towards each other, and having velocities of approach v_2 and v_3 respectively at the instant of impact. If P be the impulsive force assumed constant during the time of contact we have

$$\left.\begin{aligned} m_2\frac{dv_2}{dt} &= -P \\ m_3\frac{dv_3}{dt} &= -P \end{aligned}\right] \quad \ldots \quad (3)$$

If α_2 and α_3 be the distances moved by the centres of the cylinders towards each other after impact we have

$$\frac{d\dot{\alpha}}{dt} = \frac{dv_2}{dt} + \frac{dv_3}{dt} \quad \ldots \quad (4)$$

$$= -\frac{P}{M}$$

$$\left[\begin{aligned} \alpha &= \alpha_2+\alpha_3 \\ \dot{\alpha} &= v_2+v_3 = v \\ M &= \frac{m_2 m_3}{m_2+m_3} \end{aligned}\right.$$

As in the usual Hertz theory of impact α_2 and α_3 may be determined from the strains obtained under static conditions. We have the vertical deflection at a distance R from a region where the pressure is p given by

$$\frac{1-\sigma}{2\pi\mu}\int\int p\,dR\,d\theta$$

If we neglect the distribution of the pressure in the area of contact—circle of radius r—we have

$$\alpha_2 = \frac{1-\sigma_2}{\mu_2}pr \quad \left[p \text{ now being the average pressure}\right].$$

Similarly

$$\alpha_3 = \frac{1-\sigma_3}{\mu_3}pr.$$

Therefore

$$\alpha = pr\left[\frac{1-\sigma_2}{\mu_2}+\frac{1-\sigma_3}{\mu_3}\right]$$

and

$$p = \frac{\pi r\alpha}{f(\sigma\mu)} \quad ; \quad f(\sigma\mu) = \frac{1-\sigma_2}{\mu_2}+\frac{1-\sigma_3}{\mu_3}$$

$$p = \frac{P}{\pi r^2}$$

with this equation (4) becomes

$$\ddot{\alpha} = -\frac{\pi r\alpha}{Mf(\sigma\mu)} \quad .. \quad .. \quad .. \quad .. \quad (5)$$

which gets integrated to

$$\alpha^{\cdot 2}-v^2 = -\frac{\pi r}{Mf(\sigma\mu)}\alpha^{\cdot 2}. \quad .. \quad .. \quad .. \quad .. \quad (6)$$

The maximum value of α for $\dot{\alpha} = 0$ is given by

$$\alpha_m = v\left[\frac{Mf(\sigma\mu)}{\pi r}\right]^{\frac{1}{2}}$$

and the corresponding maximum pressure by

$$p = \left[\frac{m_2 m_3}{\pi r^3 f(\sigma\mu)(m_2+m_3)}\right]^{\frac{1}{2}} v$$

when $m_2 \ll m_3$ as is generally the case in these experiments on explosives, we have

$$p = \left[\frac{m_2}{\pi r^3 f(\sigma\mu)}\right]^{\frac{1}{2}}.v \quad .. \quad .. \quad .. \quad .. \quad (7)$$

v_3 being equal to zero, v is the velocity v_2 acquired by the anvil due to the impact. From standard laws of colliding bodies it is given by

$$v_2 = \frac{m_1(1+e)v_1}{(m_1+m_2)}$$

e being the coefficient of restitution under the conditions of experiment, m_1 the weight of the falling ball, v_1 its velocity at the instant of impact. Putting the value of v_2 in equation (7) and assuming a constant value of p we have the mass versus height relation for fifty per cent explosion efficiency given by

$$m_1 h = \frac{p^2\pi r^3 f(\sigma\mu)}{2g(1+e)^2 f(m_1 m_2)} \quad .. \quad .. \quad .. \quad (8)$$

g being the acceleration due to gravity and

$$f(m_1 m_2) = \frac{m_1 m_2}{(m_1+m_2)^2}.$$

Table 1 gives the values of the pressures as calculated by equations (2) and (7) taking data from certain experiments, source being mentioned underneath each explosive. Figure 1 shows the mass versus height relation as expressed by

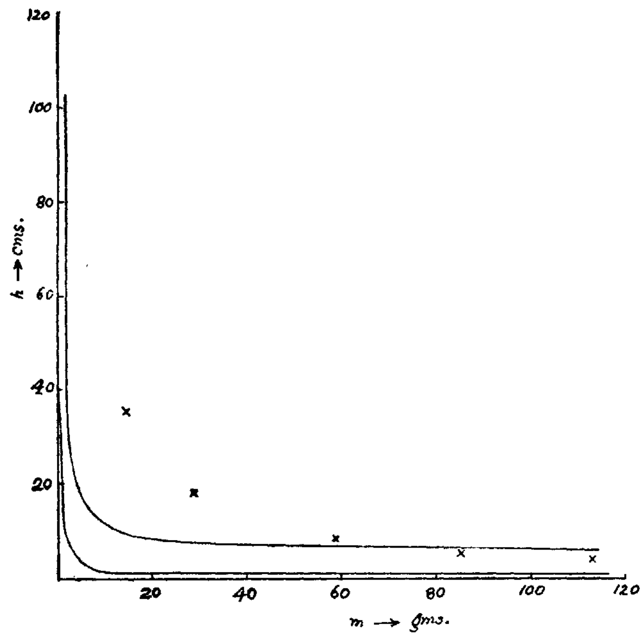

FIG. 1. The above shows the relation between the mass m and its height of fall h to give fifty per cent explosion efficiency. The full curves correspond to the two sets of elastic constants. The experimental points are shown in crosses.

equation (8). The two curves correspond to the two values of the function of $f(\sigma\mu)$ —the experimental points are shown in crosses, as taken from the data of Taylor and Weale (1932). The value of p has been taken to be the experimental value of the pressure for fifty per cent explosion efficiency, as measured by Hollies *et al.* (1953). The value of the coefficient of restitution will depend on the mass m_1 and the height h, but in these calculations a constant value equal to 0·7 has been assumed.

The equation for p above leads to another interesting result. It is known from well controlled experiments of Bowden *et al.* that the initiation in most of the explosives is thermal in character and occurs among other causes by the compression of a gas bubble entrapped in the body of the explosive. One of the several experimental evidences in support of this hypothesis is the work of Bowden and co-workers (1947) on the high pressure apparatus showing that the probability of explosion depends upon the initial pressure of the gas surrounding the explosive layer. The equation (8) leads to a verification of this observation. If p_0, T_0 be the initial pressure and temperature of the gas surrounding the explosive and T_1 the final temperature required for explosion we have

$$T_1 = T_0 \left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (9)$$

TABLE 1

Explosive	Weight of the ball, gms.	Height of fall of 50% explosion efficiency	Area of cross-section of the anvil, sq. cm.	Calculated pressures atmospheres				Experimental pressures atmospheres
				Method 1		Method 2		
				1	2	1	2	
Mercury fulminate (2, 3, 7)	14·2	35·6	0·026	12419	6659	10128	3791	1540-1925
	28·4	18·0		—	—	7876	2955	
	56·8	8·9		—	—	**5827**	**2181***	
	85·2	5·8		—	—	**4774**	**1787**	
	113·4	4·3		12065	6469	**4166**	**1560**	
	225	100	1·25	3011	1616	**2130**	**789**	
	44·64	64	0·1	9900	5300	—	—	
No explosive (2)	44·64	64	0·1	9900	5300	—	—	**6160-7700**
Nitroglycerine (4)	112	12		**527**	**283**	—	—	† 400- 800 (5) 600 (6)
PETN (4)	1860	16	1·25	4099	2200	896	328	—
		40		7083	3802	1416	518	—

* The figures in bold correspond to those showing agreement between the experimental and theoretical values.

† These values are for pressures obtained in general in liquid films and are not the values for these particular data.

γ being the ratio of the specific heats of the gas concerned. Putting the value of p from equation (8) we have

$$hp_0^{-2} = \frac{\pi r^3 f(\sigma\mu)}{2g(1+e)^2 f(m_1 m_2) m_1} \left(\frac{T_1}{T_0}\right)^{\frac{2\gamma}{\gamma-1}} \quad \cdots \quad \cdots \quad \cdots \quad (10)$$

This gives a relation between the initial pressure of the gas p_0 and height of fall for 50 per cent explosion efficiency. Regarding the RHS of equal (10) constant we have h *vs* p_0 relation given by

$$hp_0^{-2} = \text{constant.} \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (11)$$

The experimental data for nitroglycerine are tabulated in Table 2.

TABLE 2

Gas	Initial pressure (Atms)	Height of fall for 50% explosion efficiency	h/p_0^2
Air	16·5	36	0·132
	25·8	98	0·147
Nitrogen	6·7	36	0·801
	10·5	98	0·889

The value of h/p_0^2 is sensibly constant for the same gas but is considerably different from air to nitrogen presumably because of a higher compression ratio needed in the case of the latter to give rise to explosion. It is interesting to note that this comes out to be so in nitroglycerine by an approach which does not bring in its flow properties as done by Eirich and Tabor (1948).

DISCUSSION

The pressures obtained in these calculations are of the same order as estimated from other considerations. The first method of approach does not take into account the impact between the anvil and the explosive. The values of the pressure calculated by this method would be comparable to those obtained without the explosive. For cases when explosive is there the second method should give better agreement. In the calculation of pressures without the explosive, taking data from Hollies *et al.* (1953) the area of contact has been taken to be 0·1 sq. cm. (the value of the apparent arc of contact). This seems to be the value of the latter between the hammer and the plane. When there is no explosive (on norite in their experiments) in the cavity and the hammer is resting in it the area of contact perhaps will be more. But this would effect the experimental and the theoretical values in the same way.

The elastic constants of explosives are not known much less under dynamic conditions. The latter will depend on the rate of loading. From the point of view of theoretical interest, therefore, one can only predict a range of height of fall of a certain mass for fifty per cent explosion efficiency. The experimental points for the higher masses of the falling ball lie within the theoretical curves. The departure for smaller masses may be due to the still higher rates of loading and the consequent value of the elastic constants still lesser than those hitherto used. The exact mass of the striking pin has not been specified by the authors. These calculations have been made for $m_2 = 3{\cdot}0$ gms.*

For cases when the initiation is due to the compression of an entrapped gas bubble (in the absence of any seemingly obvious cause, for example the last two cases in Table 1) the temperature rise will be in the neighbourhood of 1,500°C.—much more than the minimum temperature required for explosion obtained by compression of air over the explosive layer. This in fact would be the case, for these two data refer to different sets of experimental conditions, the later involving no impact at all. This would modify the values of pressures and the consequent rise in the temperature of the air bubble, reported in Murgai (1954). The conclusion regarding the small rise in temperature of the explosive itself by adiabatic compression by pressures obtained in these experiments remains of course unaltered.

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Abstract

Pressures generated on the explosive layer, under conditions of experiments on the impact sensitivity of explosives, have been calculated making use of the Hertz theory of impact, taking data from certain experiments on explosion. In the absence of any knowledge of the elastic constants of explosives under dynamic conditions of loading calculations have been made for two sets of elastic constants one for steel to steel impact and the other for steel to a solid having elastic constants one-tenth that of steel. The experimental pressures lie between these two values. A reinterpretation of the results leads to a relation between a mass m and its height of fall h for 50 per cent explosion efficiency. The variation of the height h and the pressure p_0 of the gas surrounding the explosive layer for 50 per cent efficiency is shown to be governed by the relation $h/p_0^2 =$ constant.

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