Defence Science Journal, Vol. 53, No. 4, October 2003, pp. 357-365

Impulsive Loading of Armour by High Explosive Squash Head Munition

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ABSTRACT

Results obtained by theoretical modelling studies involving classical stress-strain theories, duly validated by experimental investigation in understanding the mechanism of impulsive loading (scabbing) and blast under dynamic and static conditions, are discussed. This concept has been used in designing a high explosive squash head ammunition being effective in defeating monolithic armour. Efforts have been made to carry out an in-depth study in understanding the mechanism of scabbing under static and dynamic (live firing) conditions. For this purpose, a one-dimensional computer code has been used to predict the spread of explosive against time on the target. The simulations were carried out using a 2-D Lagrangian hydrodynamic code for scabbing effect. The blast effect that follows under static and dynamic conditions has also been studied. Blast parameters have been computed in terms of TNT equivalent and compared with experimental results. The events occurring during impulsive loading of 135 mm monolithic rolled homogenous armour have been illustrated.

Keywords: HESH ammunition, impulsive loading, blast, dynamic loading, static loading, high explosive squash head munition, explosive reactive armour, scabbing, spalling, fracture mechanics

1. INTRODUCTION

The kinetic energy ammunition has been chosen as the primary ammunition for main battle tanks (MBTs) throughout the world for causing severe structural damages to the over fortified armour. Designing secondary munitions for use with MBTs has become a complex art. From several novel concepts that have been investigated to couple anti-armour capabilities with increased/improved lethality and blast effects (antipersonnal), the choice of high explosive squash head (HESH) ammunition emerged as a logical solution to this problem. It has the logistic advantage that it is very effective in defeating monolithic armour, reinforced structures (concrete) and other secondary targets by blast and fragmentation. It has the added advantage that it's performance remains unaffected over a wide range of angles of attack. Its advantage in neutralising advanced explosive reactive armour (ERA)[1-3] over HESH ammunition is being actively debated[3].

The functioning of this ammunition results in a contact explosion of the high energy material on the armour. This, in turn, results in an intense shock wave being transmitted into the armour/reinforced (concrete) structure (impulsive loading). The reactive armour rather reacts very differently to impulsive loads than to static loads[4-9] and the fracture pattern of a body broken up by an impulsive loading does not resemble the statically loaded counterpart. The striking effect produced by this transient compression stress wave of high intensity is scabbing when it exceeds the tensile strength of the material.

Revised 15 March 2002

Scabbing, sometimes called spalling, is the fracturing of a material near one of its free surfaces, which is relatively far away from the area of application of the pressure (stress) impulse. The mechanism of spalling has been known for decades[4-5] and is being used as an anti-armour weapon concept. However, to date, the impulsive loading of armour has not been reported in a detailed and organised manner, and only fragmentary reports have appeared in the literature[10-16].

The calculations based on these models, sometimes, miss many of the subtleties associated with the phenomena during actual dynamic impulsive loading (live firing) conditions.

This paper discusses efforts directed at understanding the mechanism of scabbing, fracture mechanics at high strain rates and blast under dynamic and static conditions. For this a combined theoretical modelling studies, involving classical stress-strain theories and experimental investigation for validation, have been undertaken.

2. MODELLING

In a projectile like HESH, both steel and explosive are present, and hence, the true yield stress is not known. A one-dimensional analysis by extending the reported work of Lee and Tuper[17], White and Grffith[18] and White[19] was done to correlate the spread of explosive with time. It is assumed that the body acts like a rigid plastic missile. There is a constant true yield stress and the target is unyielding. It is also assumed that the two modes of behaviour are possible when the shell impacts the armour, viz., flowing impact mode (ductile material spatter or flow parallel to the target surface) and mushrooming mode (bulging of nose portion takes place but there is no flow of material parallel to the target) occur. These modes of material flow are based on critical impact velocity (V_i). If $V_i > \beta$, flowing impact mode occurs, otherwise mushrooming mode becomes predominant[19]. The latter phase is likely to last till the projectile length or velocity becomes negligibly small. β is given by

$$\beta = (\sigma_y \ / \ \rho)^{1/2}$$

where σ_y is the true yield strength and ρ is the density of the material. In flowing impact mode, material flows parallel to the target surface. The velocity along the surface is determined to estimate the diameter of explosive spread.

For scabbing effect, the simulations were done using 2-D Lagrangian hydrodynamic code that includes yield strength of materials effects. The strain rate-independent Steinberg–Guinan model has been used for relating the tensile stress and shear modulus to the temperature, equivalent plastic strain and pressure[20]. Explosive burn is handled using a programmed burn model[21]. A crack growth (void growth spallation) model[22] has been used to simulate the spallation process. This model is based on the assumption that spallation occurs due to the nucleation and growth of voids in the material. This model calculates the damage parameter or distention ratio (α), which is related to porosity (ϕ) or void volume as given by

$$\phi = 1 - (1 \ / \ \alpha)$$

As the value increases, ie., void volume grows, the strength of material degrades. The simulation monitors the value of α and dynamic tensile strength. The model predicts the spallation to happen, whenever α has a peak value and the yield strength degrades to half of the initial value. The validity of this crack growth model has been verified against the published spall data[10-16].

When the shell detonates at a slight miss distance from the target, the blast impulse produced is also considered as a lethal damage mechanism. This high energy blast effect[23-30] provides a damage mechanism that can destroy targets[25,27,28,30]. The pressure pulse quickly slows down due to friction and work done on the atmospheric air. A fairly good qualitative and quantitative accounts of these phenomena are available[23,24,27,28] in the literature.

The work of Fano[23] Fischer[24] and Held[27-28] are being widely used in quantifying blast phenomena. Fano's work focused on differentiating between kinetic energy lost in the case and remains in the detonating gases after the case breaks up. His concept of equivalent charge weight relates the total available energy to the total energy in the blast, with the total explosive charge weight as a function of energy lost through the shell[23].

A computational model based on relationship postulated[23,24,27,28] by the authors was made in conjunction with the experimental program to obtain blast parameters. Equivalent charge, and hence, TNT equivalent[23,30] was calculated from these models.

3. EXPERIMENTAL PROCEDURE

For modelling spallation, complete material data for rolled homogenous armour was not available. The equation of state of mild steel and the Steinberg –Guinan coefficients for SS-304, corrected for the normal yield stress and shear modulus of published mild steel and crack growth parameters for armco iron were used.

Three' equivalent bare charges (Comp-B) of diameter 100 mm, 150 mm and 200 mm, representing worst, medium, and modelling spread diameters (height adjusted to constant charge weight available in dynamic testing) were prepared and detonated statically on a 135 mm thick mild steel block. Contact explosion was ensured using a thin plastic explosive film between the surface of the metal and the bare charge as shown in Fig. 1.

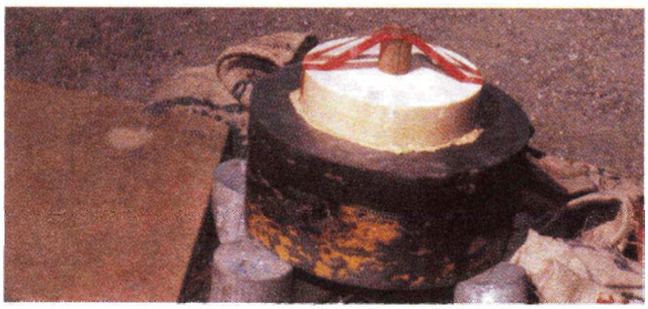

Figure 1. Experimental layout of bare charge of 200 mm modelling spread diameter.

For dynamic trials (live firing), required number of experimental projectiles were manufactured from steel to specification JSS–9510-1 Gr SSF–30 and press filled with 3 kg of RDX/WAX 88/12 composition. The projectile had charge-to-mass (C/M) ratio of 0.34 and length-to-diameter (L/D) ratio of 3.33. A general assembly of the projectile is shown in Fig. 2.

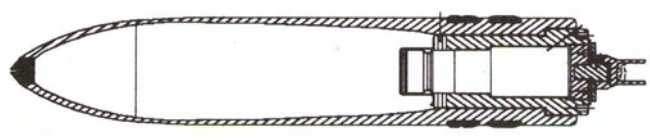

Figure 2. High energy squash head shell assembly

Three Fastax cameras were used to photograph events associated with the impulsive loading of armour under dynamic (live firing) condition on striking the target. Velocity and delay of scabs were studied on a vanguard motion analyser.

For blast measurements, a 4-channel blast recorder with ancillary instruments were used. The shells were suspended in the air and were fired electrically in the centre of a layout with four blast gauges kept at a level and pointing towards the centre of the shell. The blast gauges were kept at 6 m and 10 m to prevent their damage.

4. RESULTS

The one-dimensional modelling analysis indicates that the spread diameter of the explosive is around 200 mm after 0.35 ms (fuse delay time) when the shell moving with 720 m/s is impacted on an unyielding target. A plot showing the variation in the spread diameter of explosive spread at different time intervals is given in Fig. 3.

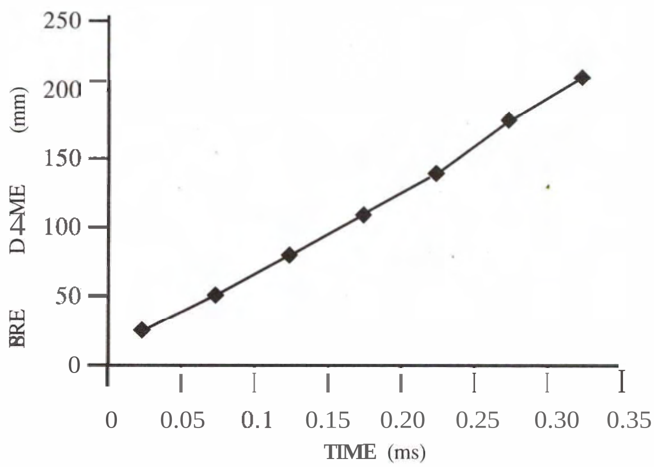

Figure 3. Plot showing the variation in the spread diameter of explosive at different time intervals.

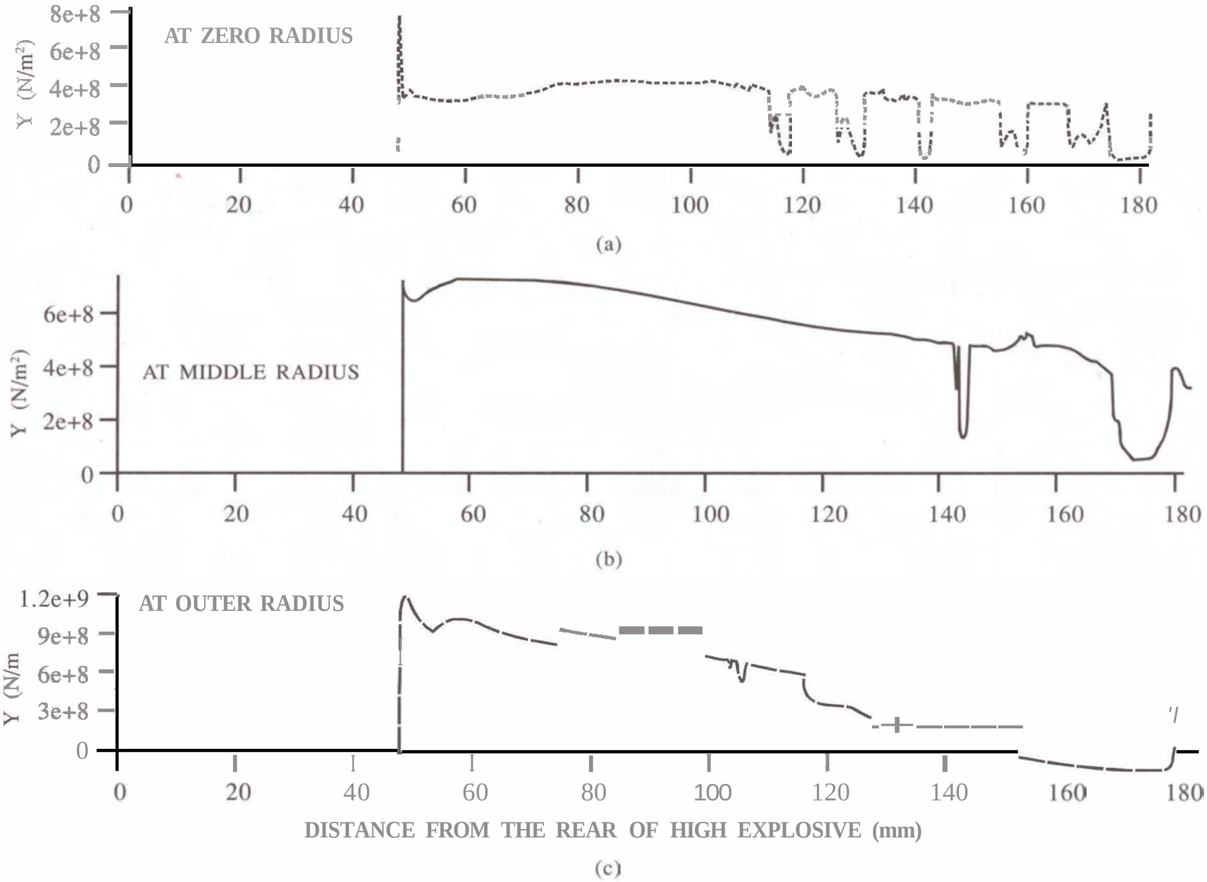

Figure 4. Variation in tensile strength with axial position at three radii under explosive loading of 200 mm high energy spread diameter: (a) on the axis, (b) at the midpoint of these extremes (r = 50), and (c) near the periphery (r = 100).

Simulations were performed for spallation process in 135 mm thick armco iron target. Results show that multiple fractures are formed along the thickness when a 200 mm diameter charge was used to impulsively load the target. Figure 4 shows the variation in tensile stress with axial position at three radii, viz., on the axis, near the periphery (r = 100), and at the midpoint of these extremes (r = 50).

It can be seen from the Fig. 4 that on the axis, the target tends to break up into as many as five pieces. At the larger radii, however, the number of fragments reduces to two. It is likely, therefore, that the periphery would tend to hold the target pieces together, yielding only two scabs, as illustrated in Fig. 5. The first and the second scabs formed have thicknesses of 16 mm and 8 mm, respectively.

The static trials (Figs 6 to 9) carried out with charges of diameters 100 mm, 150 mm and 200 mm revealed that depressions of diameters 120 mm, 180 mm, and 250 mm were formed on the explosive contact surfaces of the plates. This shows that the depression diameter is 1.2 times the

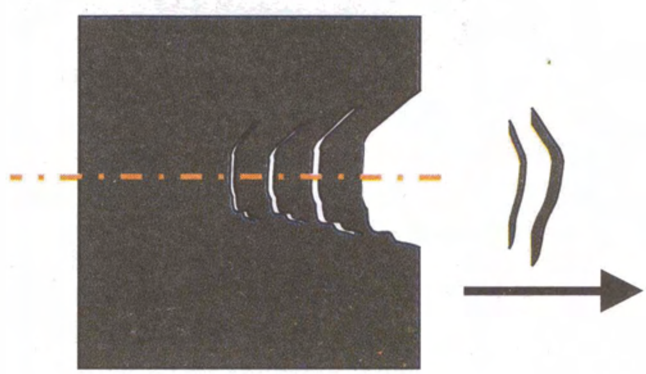

Figure 5. Multiple fractures along the axis

Figure 6. Depression formed from 200 mm dia[redacted]ter charge (front face).

Figure 7. Multiple scabs from 200 mm diameter charge (rear face).

Figure 8. Scab from 150 mm diameter charge

charge diameter (Fig. 6). The depression noticed in the dynamic firing is 260 mm. These observations prove that the spread diameter calculated theoretically matches with the experimental results. Multiple spallation, as predicted during simulation, was observed in 150 mm and 200 mm diameter charges (Fig. 7).

A large number of dynamic (live firing) trials were carried out on rolled armour plate of 135 mm thickness for scabbing. It was observed that a depression of over 250–280 mm was formed due

Figure 9. Scab from 100 mm diameter charge

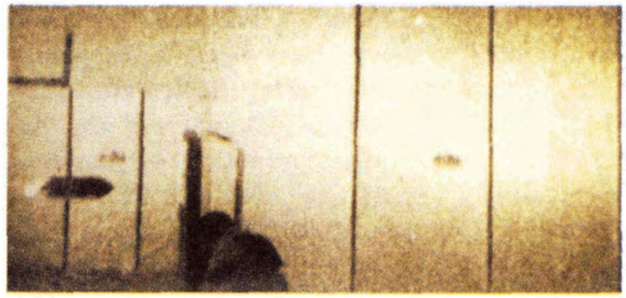

Figure 10. Projectile launched

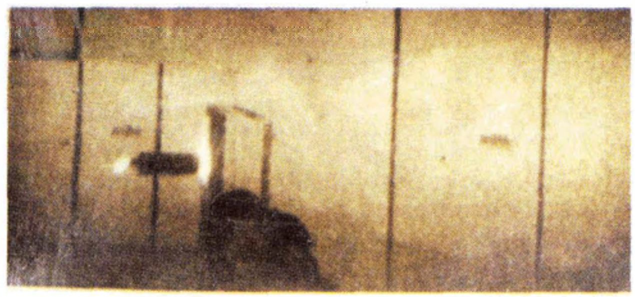

Figure 11. Shell on impact 0.7 ms

to contact explosion on the front side of the plate. The recovered scab weighed 9.5 kg (average). The thickness of the scab obtained measured approx. 16–20 mm with an average velocity of 140 m/s. No traces of secondary scabs were observed.

Several shells were fired at different impact velocities and scabbing was observed only when the impact velocity was approx. 700 ± 50 m/s. It is possible that beyond this impact velocity, the projectile is disintegrating, resulting in impaired functioning. Sequential events recorded through camera during dynamic trials (live firing) are given in the Figs 10-12.

Figure 12. Scabbing after 5 ms

A representative sample of the scab recovered and damage caused to the rear of the armour plate are given in the Figs 13 and 14. Since peak overpressure could not be measured very near to the point of initiation, efforts were made to calculate it using Fano's relation.

Figure 13. Recovered scab

Calculations based on this relation show that charge weight equivalent to one-third of the bare charge is only available for producing blast effect

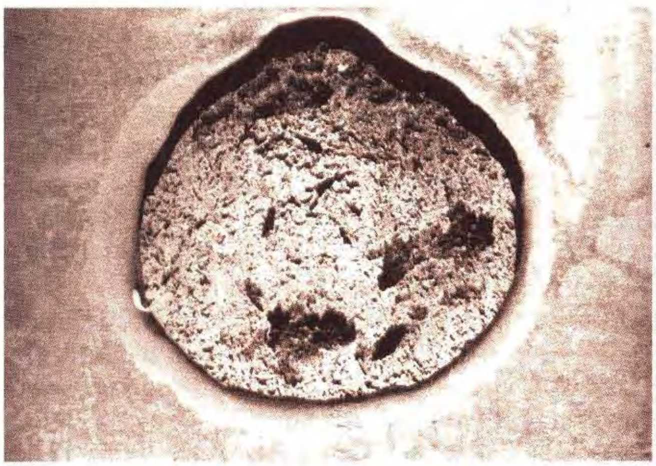

Figure 14. Rear of armour

and the rest is used to impart kinetic energy to the shell body. Blast parameters were calculated in terms of TNT equivalent charge[23,30]. A plot of the average peak overpressure obtained experimentally along with those based on modelling are given in Fig. 15. It can be seen from the figure that the values match fairly well with the experimental results.

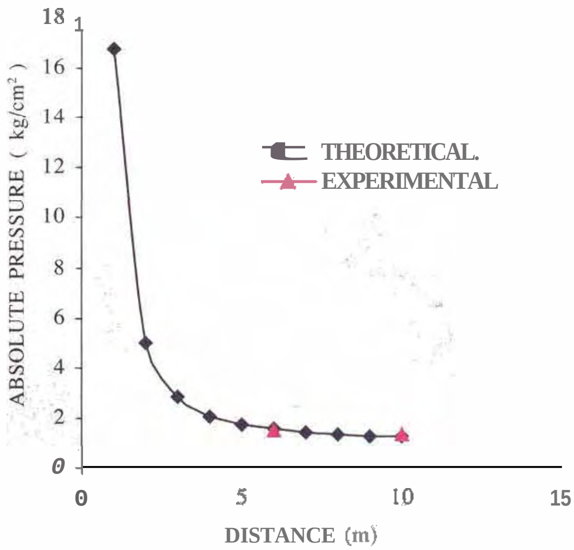

Figure 15. Plot of peak pressure versus radius

The blast impulse and the blast energy density (Table 1) have been calculated based on relations[23,27,28,30]. This energy is a fair measure of the amount of total energy absorbed into the target to cause deflection or collapse of the target.

Table 1. Blast energy density and blast impulse

Distance (m)	Blast impulse ($kgf/cm^2 s^{-1}$)	Blast energy density (MJ/M^2)
1	4.1760	5.2883
2	2.0880	0.6610
3	1.3920	0.1959
4	1.0440	0.0826
5	0.8352	0.0423
6	0.6960	0.0245
7	0.5966	0.0154
8	0.5220	0.0103
9	0.4640	0.0073
10	0.4176	0.0053

5. DISCUSSIONS

Modelling studies reveal that the spread diameter of the explosive is around 200 mm when a shell is impacted. A depression over 260 mm diameter was observed when the shell detonated on the front side of the armour plate during dynamic (live firing) trials. The depressions over 120 mm, 180 mm, and 250 mm diameter were observed when charge of diameters 100 mm, 150 mm, and 200 mm, respectively were detonated statically. Since the depressions were formed on the plates in both the static and the dynamic trials, and the values obtained by modelling nearly matched, it is presumed that this one-dimensional model can be used to predict the spread of high explosive assuming that the high explosive is always contained in the shell even during flowing impact mode. It is likely that the spread of the high explosive occurs only in the flowing impact mode and thickening of the explosive spread takes place in the mushrooming mode.

A 2-D simulation of the spallation process in 135 mm thick armco iron target indicates that multiple fractures along the thickness are formed in the region near the axis of symmetry when a 200 mm diameter charge was used to impulsively load the target. However, as one moves towards the region of larger radii, the number of scabs reduces to two. The outer region with a relatively lower degree of fracture is likely to hold together the rest of the target pieces. Thus, the target as a whole should yield only two intact scabs. It can also be seen from Figs 4(a) and 7 that higher degree of fracturing has occurred near the axis of symmetry. These experimental observations are in good agreement with the modelling results.

Obrien and Davies[6] and Rhineheart[9] have postulated scabbing phenomenon in terms of net tensile stress and fracture stress. According to them, spallation occurs when the level of stress within the wave is more than double the critical normal fracture stress of mild steel. It is possible that multiple spallation occurs when the first spall is generated instantaneously due to stress wave and the reminder of the wave finds itself impinging on freshly created free boundary surface. This process continues till the stress level reduces to a value less than the critical value[5].

However, in this study, an attempt has been made to understand the mechanism of scabbing and fracture mechanics using void growth model[21]. Results obtained are close to the experimental observations.

6. CONCLUSIONS

The one-dimensional model has been experimentally verified by extending the work of Lee and Tuper[17], White and Grffith[18] and White[19] to correlate the spread of explosive against time. This model can be used to predict the spread of explosive against time in the case of munitions of this type, assuming that the explosive is always contained in the shell even during flowing impact mode.

Results from 2-D Lagrangian hydrodynamic code compares well with the published spall data and present experimental data. The crack growth model used to simulate the spallation process gives results that are in agreement with the experimental findings when corrected for rolled homogeneous armour (RHA) data and the authors opine that this code can be used for modelling scabbing phenomenon.

The present study has paved the way for a better understanding and updating the concept of impulsive loading of armour (scabbing) phenomenon.

ACKNOWLEDGEMENTS

Authors are grateful to the Director, Terminal Ballistics Research Laboratory (TBRL), Chandigarh, for his guidance and permission to conduct trials and also to Pankaj K. Choudha for his assistance in modelling and coding.

REFERENCES

1. Challenger 2: A step toward the next generation. *Def.* Armament Inter., 1991, 105, 54-56.

2. Miller, David. UK Forces in the Gulf War. Military Technology, 1991, **15(7),** 39-50.

3. Murray, Hammick. HESH–a possible counter to ERA. *Janes Def.* Weekly, 11 November 1989, 1029.

4. Rinehart, J.S. & Pearson, J. Behaviour of metals under impulsive loads. American Society for Metals, Cleveland, 1954.

5. Rinehart, J.S. & Pearson, J. Explosive working of metals. Pergamon Press, 1963.

6. Obrien, J.L. & Davis, R.S. Response of metals to high velocity deformation. Metallurgical Society Conference, 11-12 July 1960.

7. Shewmon, P.G. & Zackay, V.F. (Eds) Response of metals to high velocity deformation. Inter Science, New York, 1961.

8. Rice, M.H.; Mcqueen, R.G. & Walsh, J.M. Compression of solids by strong shock waves. In Solid state physics, edited by Seitz and Turnhill. Vol 6. Academic Press, New York, 1958.

9. Rinehart, J.S. Some quantitative data bearing on the scabbing of metals under explosive attack. *J.* Appl. Phys., 1951, 12, 555-60.

10. Cooper, P.W. Explosive engineering. VCH Publications Inc., New York, 1966,

11. Kanel, G.I.; Razorenov, S.V. & Fortov, V.E. Cleavage strength of metals over a wide range of loadings durations. Sov. Phys. Dokl., 1984, **29(3)**, 241-42 (Russian),

12. Kanel, G.I. & Shcherban, V.V. Plastic deformation and cleavage rupture of armco iron in a shock wave. Combust. Explos. Shock Waves, 1980, **16(4)**, 439-46.

13. Razorenov, S.V.; Kanel, G.I.; Anufriev, V.G. & Lostutov, V.F. Deformation and failure of structural steels in pulsed loading. Translated from Problemy Prochnosti, 1992, 42-48. Tech Report DSWA-TR-96-77-V2. NTIS Report No. (ADA 362759).

14. Lee, E.H. & Tuper, S.J. Analysis of plastic deformation in a steel cylinder striking a rigid target. *ASME* **J.** Appl. Mech., 1954, 21, 63-70.

15. White, M.P. & Griffith, L. The propagation of plasticity in uniaxial compressions. *ASME* **J.** Appl. Mech., 1958, 15, 256-60.

16. White, M.P. Impact force of a rigid plastic body. Transactions *ASME*, 1984, 51, 102-06.

17. Steinberg, D.J. & Guinan, M.W. A high strain rate constitutive model for metals, Lawrence Livermore National Laboratory, 1978. Report No. UCRL-80465.

18. Dobratz, B.M. & Crawford, P.C. Lawrence Livermore National Laboratory explosive handbook–properties of chemical explosives and explosive simulants. Lawrence Livermore National Laboratory, USA, 1981.

19. Johnson, J.N.; Gray, G.T. & Bourne, N.K. Effect of pulse duration and strain rate on incipient spall fracture in copper. **J.** Appl. Phy., 1999, **86(9)**, 4892-901.

20. Lloyd, R.M. Blast warhead. In Progress in Astronautics and Aeronautics, 1998, pp. 261-63.

21. Macfadzeon, R.H. Surface-based air defence system analysis. Artech House, Boston, 1992.

22. Greenspan, J.E. Damage to structures by fragments and blast. J. G. Engineering Research Association, June 1971.

23. Kinney, G.F. & Graham, K.J. Explosive shocks in air. Ed. 2. Springer-Verlag, New York, 1986.

24. Held, M. Similarities of shock wave damage in air and water. Prop. Explos. Pyrotech., 1990, 15, 149-56.

25. Held, M. Blast waves in free air. *Prop. Explos.* Pyrotech., 1983, 8, 1-7

26. Engineering design handbook: Principles of explosive behaviour. Army Material Command, Washington D.C., 1972. AMCP 7-6-180, HQ, USA.

27. Berthelot, M. Explosives and their power (English translation by Hake and Macnab). John Murray Publication, London, 1892.

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