

Modelling of Fracture Processes in the Ballistic Impact on Ceramic Armours

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Summary: This work examines the essential physical processes in the perforation of metal backed ceramic armours which include projectile erosion, fracture of the ceramic tile and ductile deformation of the metal backing plate. The impact of projectiles onto alumina and aluminium nitride ceramic materials is studied experimentally and numerically. Observations were performed using an X-ray shadowgraph technique to obtain accurate data of the penetration process at different times. From the examination of computer simulations and corresponding impact experiments a simple *analytical model* is developed by assuming some hypotheses simplifying the actual mechanisms of the penetration process. Material description is simplified by using simple equations and a few material parameters easily obtained experimentally, such as the elastic modulus, the compressive and tensile strength and the rupture strain.

Résumé: Ce travail examine les procès physiques essentiels qui concernent la perforation des blindages céramique/métal en incluant dans un modèle analytique l'érosion du projectile, la fracture de la céramique et la déformation plastique de la plaque métallique. L'impact de projectiles sur des plaques d'oxyde d'aluminium et de nitride d'aluminium est étudié expérimentale et numériquement. Pour obtenir les données expérimentales un appareil photographique à rayons X a été utilisé, permettant observer avec précision le procès de pénétration. À partir de l'analyse des simulations numériques et des données expérimentales un modèle analytique a été développé en assumant une grande simplification des mécanismes de perforation. Le comportement mécanique des matériaux est simplifié en faisant appel à des équations constitutives simples avec quelques paramètres facilement accessibles expérimentalement comme le module d'élasticité, la résistance à compression et la déformation maximale.

1. INTRODUCTION

Weight is one of the most relevant parameters to be considered in armour designing, because many systems requiring protection against missile impact are mobile. For instance, military vehicles, tanks, airplanes and helicopters must be protected against all kind of projectiles and personnel of armed forces and police bodies may also require utilisation of lightweight body armours and helmets.

When such systems are impacted by modern AP (armour piercing) projectiles, the utilisation of dual hardness armour has improved ballistic protection with respect to monolithic metallic armours, by combinations of a hard outer layer with a softer inner layer. Among the different combinations, the use of a ceramic tile backed by an aluminium plate has proved to have highest mass effectiveness against armour piercing projectiles. A typical sketch is shown in figure 1.

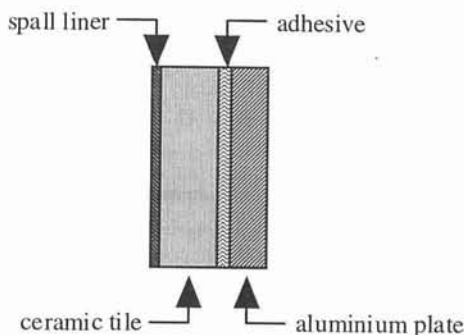


Figure 1. Sketch of a typical ceramic/aluminium armour.

Composite armour designing is a complex task that use to be helped by using different design tools. Among them, empirical methods are obviously the most accurate ones, the disadvantage of them being that they are just valid for the special system (projectile/target) tested, any change in the system usually requiring the repetition of the whole testing programme. An alternative approach is the utilisation of numerical methods, which may simulate correctly the full process of penetration of projectiles into ceramic/metal armours. However, commercial hydrocodes require the knowledge of constitutive equations of the materials involved at high strain rates, which usually are not fully available, thus some degree of parametric approximation is necessary for the use of computer hydrocodes. On the other hand, numerical simulation of impact problems is expensive and time consuming, so that the number of systems to be analysed must be kept reduced. Analytical methods to simulate impact penetration appear as useful tools for armour designing due to their simplicity and computation speed. Material description in analytical models is achieved by simple constitutive equations and a reduced number of parameters easily obtainable experimentally, such as Young's modulus, compressive strength and ultimate tensile strain. Obviously, the main disadvantage of these models with respect to numerical methods is the lower accuracy of results.

Up to now only three analytical models have been developed to simulate high speed impact on ceramic/metal targets (Florence [1], Woodward [2] and den Reijer [3]). All of them are unidimensional and all of them analyse only *normal impact* of projectiles against ceramic/metal targets. In Florence's model, energy balance for the projectile/target system is considered to derive the ballistic limit by a single equation. Woodward's and den Reijer's models, developed more recently, propose a set of equations governing the main physical phenomena taking place during the penetration process, which can be integrated over time to provide the evolution of the system. Analytical results obtained with all three models are fairly accurate for impact analysis of low caliber projectiles such as the 7.62 AP projectile, which has a steel core and impact velocity around 800 m/s. However, when they are used for analysing impact of medium caliber projectiles, with tungsten core and impact speed around 1200 m/s, analytical results overestimate the actual protection capacity of the armour, as can be seen in figure 2, where residual velocities of 20 APDS projectiles are plotted both as derived from Woodward's and den Reijer's models and obtained in experimental tests performed by Empresa Nacional Santa Bárbara (Briales et al. [4]). Therefore, a new analytical model has been developed, able to simulate accurately the penetration process of medium caliber projectiles into ceramic/metal targets. The description of the model has been published elsewhere (Sánchez-Galvez et al. [5] and Zaera [6]). In this paper, the mechanisms controlling the penetration of projectiles in ceramic/metal targets are discussed.

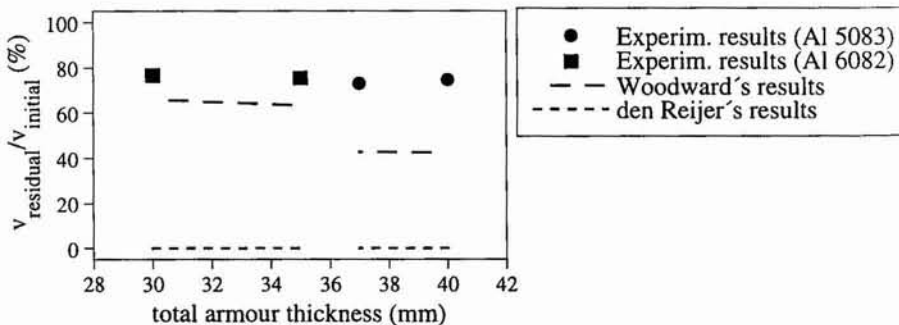


Figure 2. Analytical and experimental results of impact residual velocities of 20 APDS projectiles on alumina/aluminium targets.

2. ANALYTICAL MODEL

The behaviour of the projectile is modelled assuming that mushrooming is negligible for tungsten core projectiles impacting ceramic/metal targets. Such hypothesis is confirmed by visual observations of

residual projectiles after perforation of the armour (see figure 3) in agreement with previous observations of Maysless et al. [7] demonstrating the erosive effect of ceramic on the projectile. Therefore, a material element of the projectile core is assumed to be rigid until its full erosion by the ceramic.

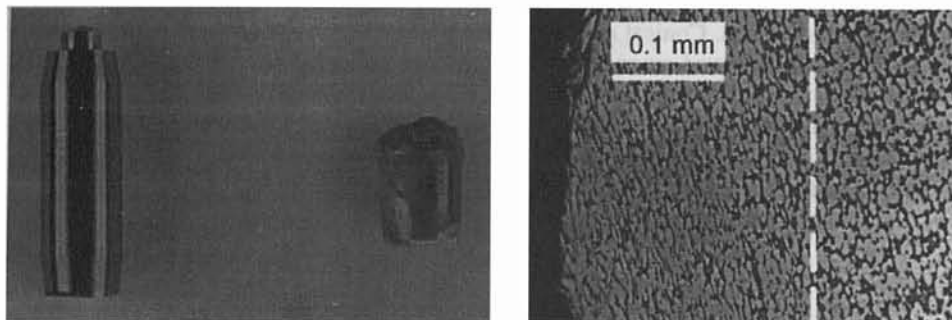


Figure 3. Left: 20 APDS projectile before and after impact on a 95% alumina/aluminium target. Right: micrograph of the projectile's tip after impact. The plastically deformed area is that to the left of the dotted line (around 0.2 mm).

The equation governing the penetration process during the erosion of projectile and ceramic is assumed to be that proposed by Tate [8] and Alekseevskii [9]:

$$Y_p + \frac{1}{2} \rho_p (v-u)^2 = Y_c + \frac{1}{2} \rho_c u^2 \quad (1)$$

where Y_p is the dynamic yield stress of the projectile, Y_c is the penetration strength of the ceramic, ρ_p and ρ_c the densities of projectile and ceramic, v the instantaneous speed of the projectile and u the penetration speed.

On the other hand, the ceramic tile is being fragmented continuously during the whole penetration process. Some authors (Wilkins [10], den Reijer [3]), however indicate that fragmentation happening during the first microseconds after the initial contact is the most relevant one on the decrease of ceramic strength. During the first stage, a stress wave propagates from the impact area creating advancing cracking front in the impact direction; this front promotes the formation of a definite set of cracks well defined in the literature (Shockey et al. [11]) called circumferential and conical. When the stress wave reaches the rear face of the ceramic tile, it begins bending, generating radial cracks that propagate in the opposite direction. The time elapsed in this fragmentation stage is assumed to be that required for all cracking fronts to travel through the tile thickness at a constant speed v_c . Such condition is expressed by the following equation (see figure 4):

$$x + s_{fradial} = h_c \quad (2)$$

where x is projectile penetration, $s_{fradial}$ is the distance travelled by the radial cracking front from the rear face of the tile and h_c is the tile thickness.

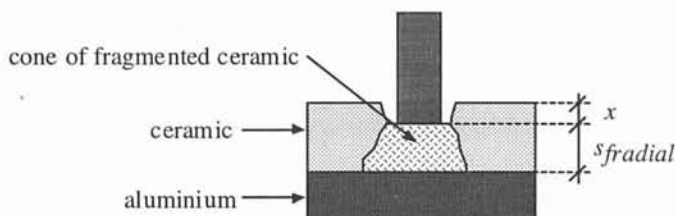


Figure 4. End of the ceramic fragmentation stage.

After ceramic fragmentation, the projectile penetrates into damaged ceramic, whose mechanical properties are lower than those of the intact ceramic. The volume of ceramic opposing the projectile penetration has a conic shape, its base distributing the pressure on a larger area of the backing metal plate. Former analytical models assumed a constant value of the semiangle of the cone between 60° and 65° for the whole penetration process. Conical cracking, however, are not limited to within that range of angles: Wilson et al. [12] have observed among ceramic fragments collected after firing tests conical cracks at much lower angles with respect to impact direction. X-ray shadowgraphs obtained by Empresa Nacional Santa Bárbara show that for medium caliber projectiles the volume of the target affected by the impact is much more concentrated around the impact point than that assumed by former analytical models (see figure 5). Therefore, a small value of the ceramic cone angle is assumed in the present model.

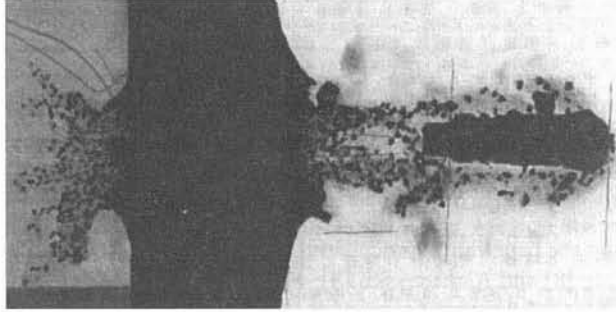


Figure 5. X-ray shadowgraph of the impact of 25 mm APDS projectile on alumina/aluminium target.

Inside the ceramic cone the velocity is assumed to have a direction coincident with the impact direction and its magnitude is assumed to vary linearly from x for the projectile/ceramic interface to w for the ceramic/metal plate interface. With such velocity distribution, the motion of the ceramic cone can be derived using the equation of momentum rate of change.

The last hypothesis of the model concerning the behaviour of the ceramic material is the assumption of the law for decrease of damaged material strength. Taking into account that the penetration strength of fragmented ceramic must be dependent upon the confinement of the ceramic tile and considering that crater formation increases the room available for fragment motion, it is conceivable that ceramic strength will be reduced following a dependency on the relative speed of the ceramic respect to the projectile. The expression adopted in the present model is:

$$Y_c = Y_{co} \cdot \left(\frac{v - w}{v_{phase1}} \right)^2 \quad (3)$$

where Y_{co} is the strength at the end of stage one, v and w are the instantaneous speeds of projectile and backing metal respectively and v_{phase1} is the projectile speed at the end of stage one. Equation (3) predicts a rapid decrease of ceramic strength with projectile penetration in agreement with experimental findings of Wilkins [10] and den Reijer [3].

Finally, the contribution of metal backing plate has been computed by using an energy balance. Following the equation proposed by Woodward et al. [13] for the energy dissipated in plastic deformation in a metal plate subjected to impact:

$$E_p = \pi h_b \delta Y_b \left(\frac{2}{3} h_b + \frac{1}{2} \delta \right) \quad (4)$$

the time derivative of the energy balance on the metal plate leads to:

$$\frac{dT}{dt} = \frac{dE_k}{dt} + \frac{dE_p}{dt} \quad (5)$$

where T is the work done by external forces and E_k is the kinetic energy of the plate. In equation (4), h_b , Y_b and δ are the thickness, yield stress and central deflection of the plate respectively.

The energy balance is limited to an effective zone, for which the velocity gradients in the impact direction are reduced thus enabling to assume a constant value of the metal velocity.

3. RESULTS OF THE ANALYTICAL MODEL

Validation of the analytical model has been carried out by means of experimental data of firing tests performed by Empresa Nacional Santa Bárbara, with low and medium caliber projectiles. For instance, figure 6 illustrates the same experimental data shown in figure 2, but now the results of the simulation with the present model are also included. As can be seen, the agreement with the experimental results is much better using the present model than those of Woodward's and den Reijer's

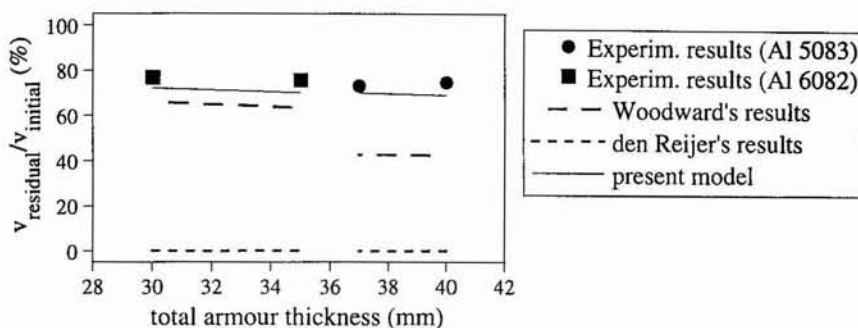


Figure 6. Analytical and experimental results of impact residual velocities of 20 APDS projectiles on alumina/aluminium targets.

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REFERENCES

- [1] Florence A. L., "Interaction of projectiles and composite armour. Part II", Stanford Research Institute, Menlo Park, California, U.S.A., (1969).
- [2] Woodward R. L., "A simple one-dimensional approach to modelling ceramic composite armour defeat", *Int. J. Impact Engng.*, 9, 4, 455-474, (1990).
- [3] den Reijer P. C., "Impact on Ceramic Faced Armours", PhD. Thesis, Delft University of Technology, (1991).
- [4] Briales C., Cortés R., Zaera R., Martínez M. A., Sánchez-Gálvez V., "An experimental and numerical study on the impact of ballistic projectiles onto ceramic/metal armours", in *Proceedings on the 15th International Symposium on Ballistics*, Jerusalem, Israel, (1995).
- [5] Sánchez-Gálvez V., Zaera R., Chocrón I. S., Martínez M. A., Cortés R., "Analytical model of ballistic impact on ceramic/metal lightweight armours", in *Proceedings on the 16th International Symposium on Ballistics*, San Francisco, (1996).
- [6] Zaera R., "Modelo Analítico para el diseño de sistemas de protección frente a impacto formados por paneles de cerámica/metal", Ph.D Thesis, E.T.S.I. Caminos, Canales y Puertos, Universidad Politécnica de Madrid (1997).
- [7] Mayseless M., Goldsmith W., Virostek S. P., Finnegan S. A., "Impact on Ceramic Targets", *Journal of Applied Mechanics*, 54, 373-378, (1987).
- [8] Tate A., "A theory for the deceleration of long rods after impact", *Jour. Mech. Phys. Solids*, 15, 387-399, (1967).

- [9] Alekseevskii V. P., "Penetration of a rod into a target at high velocity", in *Combustion, Explosion and Shock Waves*, 2, Faraday Press, New York, USA, (1966).
- [10] Wilkins M. L., "Mechanics of Penetration and Perforation". *Int. J. Impact Engng.*, 16, 793-807, (1978).
- [11] Shockey D. A., Marchand A. H., Skaggs S. R., Cort G. E., Burkett M. W., Parker R., "Failure phenomenology of confined ceramic targets and impacting rods", *Int. J. Impact Engng.*, 9, 3, 263-275, (1990).
- [12] Wilson D., Hetherington J. G., "Analysis of Ballistic Impact on Ceramic Faced Armour using High Speed Photography", en *Proceedings Lightweight Armour System Symposium*, Royal Military College of Science, Cranfield, England, (1995).
- [13] Woodward R. L., O'Donnell R. G., Baxter B. J., Nicol B., Pattie S. D., "Energy Absorption in the failure of ceramic composite armours", *Materials Forum*, 13, 174-181, (1989).