ANALYTICAL AND NUMERICAL MODELLING OF FAILURE OF CERAMIC/METAL PANELS DUE TO BALLISTIC IMPACT

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ABSTRACT

Analysis of penetration mechanics of kinetic energy projectiles into ceramic/metal panels is a difficult task. It can be faced either by analytical models or by numerical simulation. This paper summarizes the use of a new analytical model as well as the description of a model of mechanical behaviour of both intact and damaged ceramics, implemented in a commercial hydrocode, for simulation of impact phenomena of kinetic energy projectiles onto ceramic/metal panels. A good agreement between analytical, numerical and experimental results is observed. Therefore the models developed can be useful tools for ceramic/metal armour designing optimisation.

INTRODUCTION

Weight is a key factor in the design of panels for ballistic protection of moving systems such as vehicles, aircrafts and personnel of security and defense corps. Hence, the interest in developing lightweight armour systems, which made great headway with the introduction of ceramic materials at the end of 1960 s, for protection against kinetic energy projectiles which were about 60% lighter than monolithic steel armours then in use [1].

This type of protection is usually composed of a tile of ceramic and a ductile backing plate, either metallic or composite. The two components are joined by a thin layer of adhesive (Figure 1). The hard ceramic tile is used to erode the head of the projectile, while the backing plate withstands the ceramic fragments and absorbs the kinetic energy of the projectile.

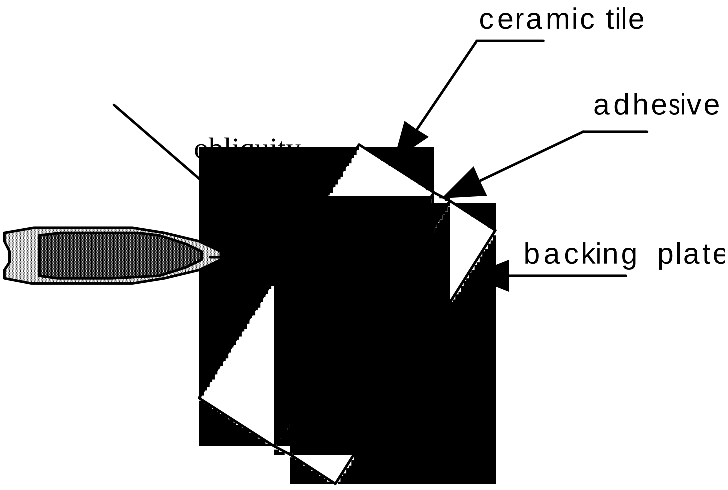


Figure 1

It is important to point out that optimal design of ceramic/metal panel for ballistic protection against a definite threat is achieved when the panel is almost perforated by the projectile, whilst this one is fully arrested or eroded, thus avoiding any damage to the protected system.

This means that optimised armour designing involves a detailed analysis of penetration mechanics, including a wide knowledge of mechanical behaviour and failure criteria of materials at high strain rates. The lack of well settled models of mechanical behaviour of advanced materials (ceramics and composites) and especially the lack of reliable failure criteria is a shortcoming to the use of hydrocodes for the numerical simulation of the penetration process of kinetic energy projectiles into ceramic faced armours [2].

Therefore, analytical models of impact simulation appear as useful tools for armour designing. Analytical models simulate the penetration process by assuming simplifying hypotheses to derive the projectile equation of motion. For ceramic/metal targets analytical models by Woodward [3], den Reijer [4] and Walker [5] have been proposed. Although results achieved with these models are fairly accurate for the impact simulation of low caliber projectiles, a poor agreement with experimental data is observed when those models are used with medium caliber projectiles [6].

At the Materials Science Department of the Polytechnic University of Madrid a new analytical model of impact simulation of kinetic energy projectiles onto ceramic/metal panels has been developed. The model has been shown to simulate accurately the penetration process of low and medium caliber projectiles into ceramic/metal targets [7].

On the other hand, a model of the dynamic behaviour of both intact and damaged ceramics as well as failure criterion of advanced ceramics has been developed [8].

This paper summarizes both analytical and numerical models and shows a few simulation results to compare to experimental data.

ANALYTICAL MODEL

The penetration process is divided into three phases (see figure 2). The first one is the fragmentation stage, which occurs after the initial contact of the projectile with the target. The second phase is the penetration stage which starts a few microseconds after contact, the conoid of comminuted ceramic in front of the projectile distributes the load on the metal backing plate while the projectile is being eroded by the ceramic. If the projectile perforates the ceramic, a third stage begins with the penetration into the metallic plate. If the projectile energy is high enough, perforation happens, if not the projectile is defeated by the armour at any of the three stages mentioned.

A more detailed description of the process, including the equations of the model are given in a previous paper by Zaera and Sánchez Gálvez [6].

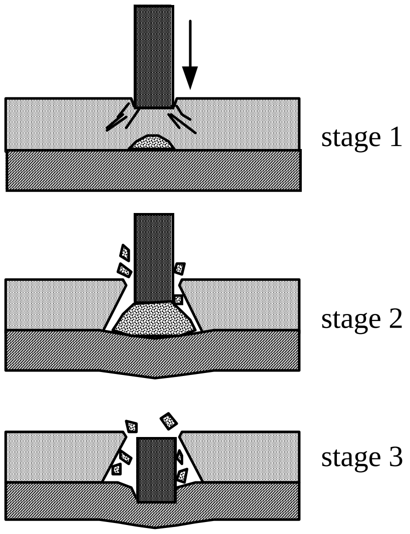


Figure 2: Stages of the penetration process

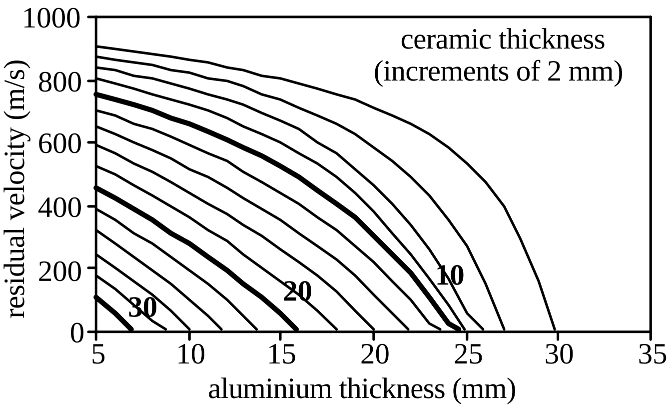


Figure 3: Minimum thicknesses of penetration.
Projectile: 20 mm APDS
Armour: Aluminium nitride/2017 T4 aluminium alloy

A Fortran code was programmed that allows a calculation at each time step of the eight variables that define the process. The result is a design tool called SCARE (aSsessment of Ceramic ARmours Efficiency). In a few seconds of calculation on a personal computer, SCARE permits a simulation of whether the panel will arrest the projectile or be perforated and in the latter case, the residual velocity and mass of the projectile.

With the SCARE code, graphics such as that displayed in figure 3 can be easily obtained. Knowing the threat and the materials to be used in the armour, the tool provides the combinations of minimum ceramic/metal thicknesses to arrest the projectile.

NUMERICAL SIMULATION

As mentioned before, a chief aspect of the performance of ceramic/metal targets is the behaviour of both intact and conminuted ceramic. Therefore, in facing impact numerical simulation a carefull modelling of ceramic is required.

The model developed by Cortés et al. [8] is elastoplastic, including a damage variable η, whose evolution equation is given by

$$\dot{\eta} = \dot{\eta}_0 (\sigma - \sigma_0) \qquad [1]$$

for $\sigma > \sigma_0, \dot{\eta}$ being null otherwise. In Eqn. 1, η is the fraction of pulverized ceramic within each cell, $\dot{\eta}_0$ is a material parameter, σ the hydrostatic stress being positive in tension and σ_0 is the hydrostatic stress for the onset of fracture. Thus, at any given time, a fraction η of ceramic will be assumed to be pulverized, whereas a fraction $(1 - \eta)$ will be considered to remain intact.

Yielding within each cell is assumed to occur when the shear stress on the octahedral plane τ fulfils the following equation:

$$\tau = (1 - \eta)\,\tau_i + \eta\,\tau_c \qquad [2]$$

where τ_i is the yield strength of the intact ceramic and τ_c is that of the comminuted ceramic.

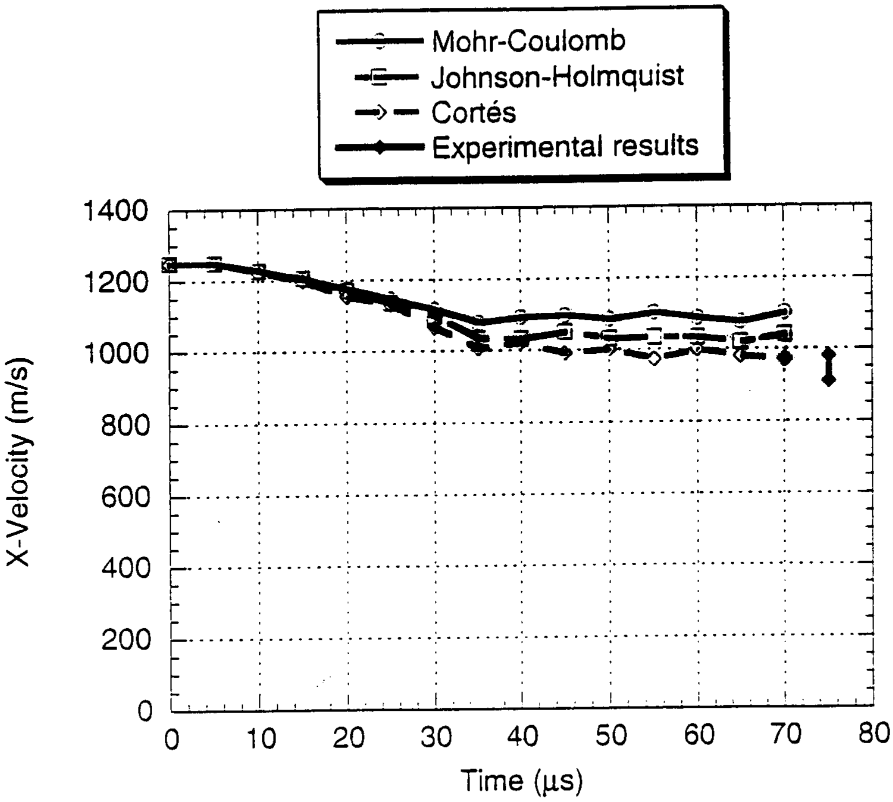
For intact ceramic, a Drucker-Prager yield criterion is assumed, whilst pulverized ceramic is assumed to verify the expression:

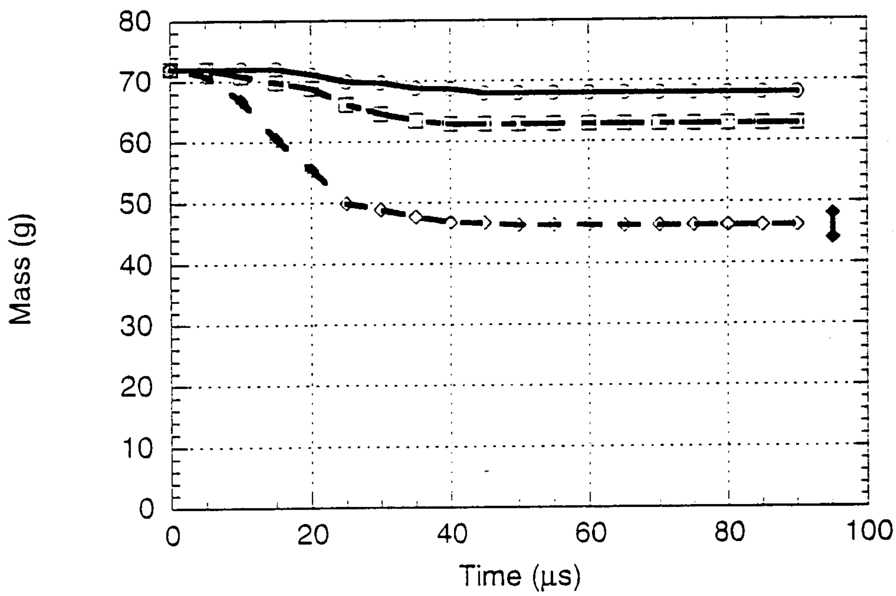
$$\tau_c = \mu\,\sigma \qquad [3]$$

where μ is an internal friction coefficient and σ the mean hydrostatic pressure, equal to that in Eqn. 1 but with opposite sign.

The model has been implemented into the AUTODYN-2D Commercial Hydrocode, and the results of numerical simulation using this model can be compared to those obtained using Johnson-Holmquist and Mohr-Coulomb models available in the library of the code.

For instance, figures 4 and 5 illustrate velocity and mass histories of 20 mm APDS projectiles impacting a panel with 20 mm thickness AD 99.5 alumina and 10 mm thickness 5083 aluminium alloy. Experimental data of residual velocity and residual mass of the projectile after perforation are also included for comparison.





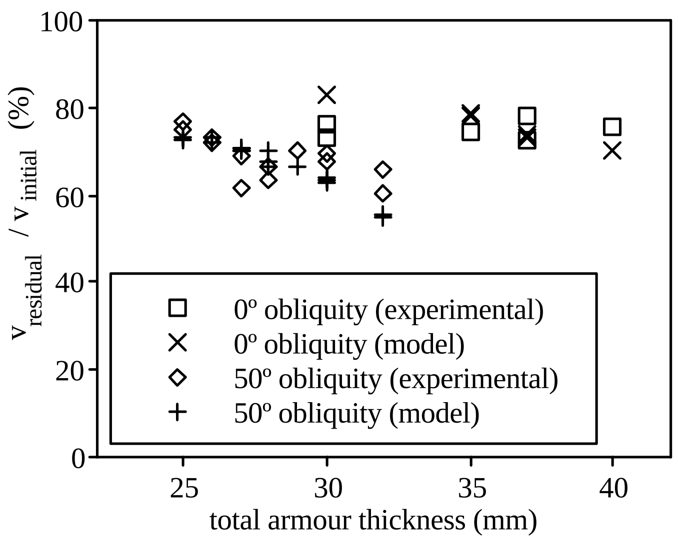
Figures 4 and 5

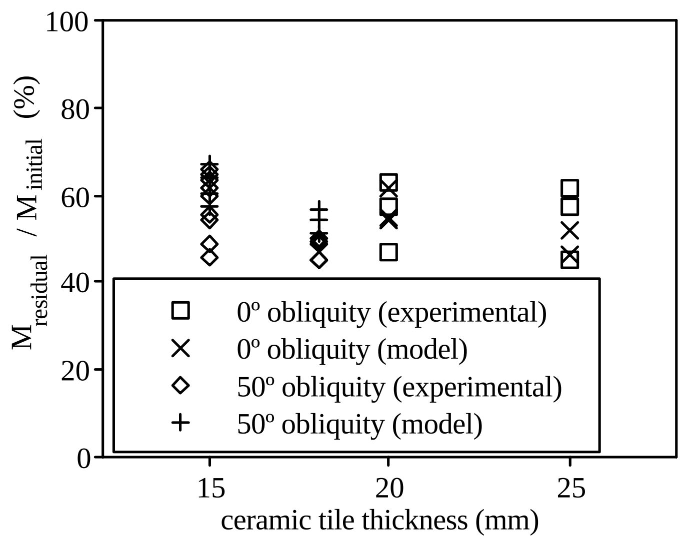
As can be seen, Cortés model leads to better results than those obtained with Mohr-Coulomb and Johnson Holmquist models.

DISCUSSION

Although a few experimental data can be shown in this paper, due to classification of firing test results, both the SCARE analytical model as well as the Cortés ceramic model implemented in AUTODYN-2D have been validated with hundreds of firing tests, using different projectiles, obliquity angles and different thicknesses of the target.

An example of the accuracy of the analytical model is shown in figures 6 and 7 where residual velocity and residual mass of 20 mm APDS projectiles after perforation of alumina/aluminium panels are shown [9]. The agreement between analytical results and experimental data is excellent and the scatter is even lower than that obtained experimentally.





Figures 6 and 7

CONCLUSIONS

At the Materials Science Department of the Polytechnic University of Madrid, a new analytical model to simulate normal and oblique ballistic impact onto ceramic/metal targets has been developed.

Also, a model of mechanical behaviour of intact and damaged ceramic subjected to impact loading has been developed and implemented into the commercial AUTODYN-2D Hydrocode.

A good agreement between analytical, numerical and experimental results is observed.

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