BALLISTIC IMPACT ON CERAMIC ARMOUR WITH DIFFERENT NOSED PROJECTILES: NUMERICAL STUDY

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ABSTRACT
A 3D finite element model has been developed in this paper for ballistic impact on ceramic targets with three different thicknesses (4, 7, 10mm) by three different nose projectiles (ogival, flat and hemispherical). The ceramic is modeled with a polynomial equation of state (EOS) using Johnson- Holmquist for the strength and JH1 for the failure model while the steel projectile is modeled with EOS shock type and Johnson-Cook Strength. This work investigates the influence of projectile head shape and the ceramic thickness on ballistic performance. It is found that the residual velocities and the amount of erosion that the projectile suffered are strongly affected by the shape of projectile head. Also the increasing the ceramic thickness leads to an increase the erosion rate and erosion amount, besides in increase in the absorbed energy.

Keywords: Finite element, Ballistic impact, Ceramic.

1. INTRODUCTION
Many ceramic materials are stiff, brittle, very hard and stronger in compression than in tension. These properties make ceramic materials suitable for armour applications. Unfortunately, when projectiles are fired onto single ceramic tiles, they are only able to provide a limited amount of protection. Their brittle behaviour and poor tensile strength cause failure and prevent them from absorbing energy. Ceramic materials are generally weak in tension but strong in compression. They can have good strength after failure when they are under compression load. So they have been used as armor plates. (Walley, 2010). Because ceramic materials are much stronger in compression than most other materials, it is not always possible to directly determine the response stress, strain, etc. for the material from experiments. Instead, the response must often be inferred from ballistic penetration tests, and this approach can introduce uncertainties. The potency to precisely model the material computationally enables a wide range of design analysis investigations to be conducted in an efficient method. To study the characteristics of ballistic penetration in thick ceramic tiles, depth-of-penetration tests are always performed Bless et al. (1987), Bless and Anderson (1993). Rosenberg et al. (1996).When ceramic tile impacted by projectile, a smashed area is formed in front of the projectile nose due to the wave interactions that generates concentrate shear stresses. To improve models design amore better armour its very important to understanding the failure mechanism that result in this pulverization.

Curran et al. (1993) present a micromechanical model for ceramic tile behaviour under impact. Rajendran and Grove (1996) and Johnson and Holmquist (1999) have present ceramic failure models which have been incorporated into EPIC code. Anderson and Walker (2000) have implemented a computational ceramic model that reproduces various experimental results of impact into thin ceramic tiles. Zaera and Galvez (1998) analytical model has been developed to describe projectile impacting a ceramic backed by a composite plate. The perforation process has been divided into three phases. This model allows the calculation of residual velocity and length of the projectile and the deflection and strain histories of the back-up material. Shokrieh and Javadvand (2008), used Ansys/LS-Dyna software, to determine the ballistic limit velocity of boron carbide ceramic backed by Kevlar 49 fiber composite material. The Hetherington (1992) equation (optimum thickness of layers) was verified for constant thickness of the armour. Abbud et al. (2010) reported an analytical model for the ballistic limit velocity from the work done for target based on the experimental observations was presented. The experimental results showed good agreement compared with Ipson and Recht equation. It was observed that increased thickness of PMMA resulted a higher absorbing energy and more resistant to ballistic impact. The objective of this paper is to investigate the impact of three types of projectiles (flat, ogival and hemispherical nose) against bare ceramic armour with different thicknesses (4.7and 10mm) by investigating the influence of projectile nose on the ceramic material on ballistic performance, also the effect of the ceramic thickness on the mechanical behaviour for both the projectile and ceramic using finite element model.

2. THEORETICAL MODEL
Projectile mass erosion is a very important mechanism by which ceramic faced armour can defeat penetration. Much of the energy that the projectile loses in the initial stages of impact is not absorbed by the armour, but is consumed by erosion of the projectile. This erosion implies a physical separation of material from the projectile so that its momentum no longer contributes to armour perforation. The process of penetration of projectile into the ceramic has been modeled here on two stages only with adoption of Zaera and Galvez (1998) model. The projectile is considered to be rigid perfectly plastic with a dynamic yield stress of Yp. The geometry here is assumed to be cylindrical.
2.1 The First Phase

The first stage is the smashing the projectile nose without penetrate of the ceramic target, besides the nucleation of cracks in a cone shape. The impact of the projectile creates compressive shock pulse which move through the ceramic thickness during this phase. This compressive wave reflects as a tension pulse which cracks the ceramic tile and fractured cone formation takes place (Figure 1).

Assume the projectile rear velocity is \( V_p(t) \), and the interfacial projectile-ceramic velocity \( V_i(t) \) is zero (at the initial impact). With exceeding the dynamic yielding of the projectile material (\( Y_p = 2.9 \text{ HV} \)), the head will erode according to Tabor (1951), and penetration resisting force is

\[
M_p \frac{dV_p}{dt} = -Y_p A_p
\]

and the projectile geometry is holding by the following:

\[
\frac{dV_p}{dt} = -\rho_p A_p V_p
\]

2.2 The Second Phase

During this phase the ceramic tile penetrates by the projectile and a fractured cone formation will takes place leading to lateral spread of the ceramic fragments. Two parts of projectile velocity can be found, \( V_p(t) \), the rear part of the projectile and \( V_i(t) \), the interfacial ceramic-projectile velocity. The rate of projectile erosion provides from the difference between these velocities, this stage involves:

2.2.1 Projectile Erosion Part

As long as \( V_p(t) > V_i(t) \), the projectile suffers erosion causing losing in projectile mass and consequent reduction in the kinetic energy. The difference between these velocities accelerate the projectile erosion, therefore the equation of projectile erosion is:

\[
Y_p + \frac{1}{2} \rho_p (V_p - V_i)^2 = R_c + \frac{1}{2} \rho_c V_i^2
\]

where \( R_c \) is the high rate resistance strength against penetration through the ceramic

\[\rho_p \text{: Projectile density}\]
\[\rho_c \text{: Ceramic density}\]

The projectile deceleration is

\[
M_p \frac{dV_p}{dt} = -Y_p A_p
\]

and the projectile weight reduction is

\[
\frac{dV_p}{dt} = -\rho_p A_p (V_p - V_i)
\]

2.2.2 Constant Mass Penetration

At the stage, the projectile velocity \( V_p(t) \) is equal to the \( V_i(t) \), where projectile erosion will stop and the mass is remained constant. From this moment, Tate’s hydrodynamic analogy can not be applied, because the interface and projectile having the same velocity. However, the rest of the projectile mass \( M_{pr} \) continues to penetrate the completely fractured ceramic. The force acting by the crushed ceramic is given by

\[
M_{pr} \frac{dV_p}{dt} = -R_c A_p
\]

One of the most important models for ceramic materials in the ballistic investigations is the Johnson-Holmaquist model. The past several years ago, these authors established three ceramic models by Johnson et al. (2003); (see Figure 2). These models (JH-1, JH-2 and JHB) are based on two sets of curves of yield stress vs pressure, i.e. sound and failed.

Each curve depends on plastic strain and plastic strain rate. A damage variable, \( D \), describes the amount of fracture. For the JH-1 and JHB model, the intact material curve is used prior to fracture \((D < 1.0)\). Once fracture has occurred \((D = 1.0)\) the failed material curve is used. The JH-2 model also has an intact and failed material curve, but the model is gradually softened as damage accumulates. More recently Johnson et al. (2003) developed the so-called JHB model. This model is an improved version of the JH-1 model. Material strength and damage are smooth analytical functions of pressure, whereas JH-1 uses a piecewise approximation. In both models the material strength does not decrease until complete damage \((D = 1)\) has occurred.

This is in contrast to the JH-2 model which gradually softens the material strength (from intact to failed) as damage accumulates.
3. NUMERICAL MODEL

With ANSYS-AUTODYN-3D commercial hydrocode a finite element model of ceramic armour system consists of the normal impact of hemispherical, ogival and cylindrical steel projectiles on to ceramic target. The steel projectiles are 7.62 mm in diameter and 20.5, 25.74, and 21.81 mm length for the flat nose, ogival nose and hemispherical nose projectile respectively, this difference in length is to maintain the volume constancy and to keep the mass equal to 7.2 gram for projectiles types (Figure 3). Its performance is similar to that of a 7.62 mm NATO armour-piercing (AP) round. The target is silicon carbide (SiC) tile of 40x40x7 mm with 144 gram.

The ceramic is modeled with polynomial as equation of state (EOS) using Johnson-Holmquist for the strength and JH1 for the failure model (see Table 1 for SiC mechanical properties). The steel projectile is modeled with EOS shock type and Johnson Cook Strength (see Table 2 For the Mechanical Properties).

Table 1 SIC Mechanical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>3215 kg/m³</td>
</tr>
<tr>
<td>Bulk Modulus</td>
<td>2.2 GPa</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>193.5 GPa</td>
</tr>
<tr>
<td>Hugoniot Elastic limit, HEL</td>
<td>11.7 GPa</td>
</tr>
<tr>
<td>Intact Strength Constant (S1)</td>
<td>7.1 GPa</td>
</tr>
<tr>
<td>Intact Strength Constant(P1)</td>
<td>2.5 GPa</td>
</tr>
<tr>
<td>Intact Strength Constant(S2)</td>
<td>12.2 GPa</td>
</tr>
<tr>
<td>Intact Strength Constant(P2)</td>
<td>10 GPa</td>
</tr>
<tr>
<td>Strain Rate Constant,C</td>
<td>0.009</td>
</tr>
<tr>
<td>Max Fracture Strength</td>
<td>1.3 GPa</td>
</tr>
<tr>
<td>Hydro Tensile Limit</td>
<td>750.000122</td>
</tr>
<tr>
<td>Damage Constant,EFMAX</td>
<td>1.2</td>
</tr>
<tr>
<td>Damage Constant(P3)</td>
<td>99.7 GPa</td>
</tr>
<tr>
<td>Bulking Constant ,Beta</td>
<td>1</td>
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</tbody>
</table>

Table 2 The Mechanical Properties For Steel Projectile

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, kg/m³</td>
<td>7896</td>
</tr>
<tr>
<td>Shear Modulus, MPa</td>
<td>8.18*10⁴</td>
</tr>
<tr>
<td>Yield stress, MPa</td>
<td>350</td>
</tr>
<tr>
<td>Hardening Constant, MPa</td>
<td>275.000031</td>
</tr>
<tr>
<td>Hardening Exponent</td>
<td>0.36</td>
</tr>
<tr>
<td>Strain rate Constant</td>
<td>0.022</td>
</tr>
</tbody>
</table>

Both ceramic tile and the projectile are modeled with uniform hexahedron solid elements. Due to the axisymmetric nature of the armour system, only one half of the projectile armour system is modeled here. (Figures 3 and 4) for Projectile and ceramic tile a Lagrange solver was used.

Figure 2 Johnson-Holmquist ceramic models

![Figure 2 Johnson-Holmquist ceramic models](image)

Figure 3 Finite element models for projectile types

![Figure 3 Finite element models for projectile types](image)
4. RESULTS AND DISCUSSION

4.1 Projectiles and Ceramic Behaviour

The shape of the projectile nose has an important influence on ceramics tile (target) behavior under ballistic impact. Figure 5 illustrates this effect, and for clear identification of this effect, we will divide it into three stages depending on the time and target thickness, respectively:

4.1.1 At Time 10µs

4.1.1 (a) Thickness 4mm

Figure 5a shows that there is a certain degree of fragmentation of the projectile with ogival nose producing more than other projectiles, as well as a little amount of erosion.

4.1.1 (b) Thickness 7mm

Through the figure, we also found that the amount of erosion for the flat nose projectile was increased. And the amount of fractured area of ceramics (for this type of projectile) is larger than the others and that the fractured area of ceramic under impact with the ogival nose projectile is the least. The reason is that the area of projectile nose has a proportional relationship with the fractured area.

4.1.1 (c) Thickness 10 mm

At this thickness and at a time of 10µs it is clearly noticed that the amount of penetration is less compared with the 7mm thickness target. Note that the fractured area of the ceramics is larger for a flat nose projectile.

4.1.2 At Time 28µs

4.1.2 (a) Thickness of 4mm

At this time, and when the ceramic tile thickness is 4 mm, it is noticed that all projectiles started penetrating more and more into the ceramic tiles (Figure 5b).

4.1.2 (b) Thickness of 7 mm

It is noticed here that the ogival nose projectile began to suffer more of erosion and the degree of penetration inside the ceramic is less than those of flat and hemispherical target.

4.1.2 (c) Thickness of 10mm

At this thickness of ceramic tile, all projectiles suffer a large amount of erosion, especially the ogival nose projectile with the observation that ceramic tiles start to fracture at the fixing area.

4.1.3 At Time 42µs

4.1.3 (a) Thickness of 4 mm

Through the Figure 5c and at this time, it is noticed that all three projectiles penetrate the ceramic with a difference in the final form of the projectile and the degree of fragmentation being greatest for the ogival nose projectile.
4.1.3 (b) Thickness of 7 mm
The size of the fractured area of ceramics tile being large and all projectiles suffering erosion, especially the ogival nose projectile as well as the fact that all projectiles penetrate the ceramic tile with an increase in the amount of fragmentation for the ogival nose projectile.

4.1.3 (c) thickness of 10mm
It is noted that the flat nose and hemispherical nose projectile penetrates the ceramic tile, while the ogival nose projectile does not occur because it suffers a large amount of erosion during the impact moment, which loses the energy needed for penetration and finally its stop with a large amount of fragmentation.

4.2 Residual Velocity
The projectile nose shape plays a large role on the value of the residual velocity. Figure 6 shows the relationship of the ratio of the residual velocity to the initial velocity (800 m/ sec) with the thickness of the ceramic tile. This ratio decreases with increasing thickness of the ceramic. The greatest reduction of this ratio occurs for the ogival nose projectile. There is an increase of the ratio for the hemispherical nose projectile followed by the flat nose projectile. This is because the ogival nose projectile suffers a severe erosion at the beginning of the impact, which in turn loses a large amount of kinetic energy making the residual velocity reach zero value.

4.3 Residual Projectile Length
As a result of the erosion of the projectiles by the ceramics at the beginning of the impact event, the residual length of the projectile varies according to the shape of projectile nose and this is what is observed in Figure 7, where the ratio of the residual to the original length changes with the thickness of the ceramic tile and the smallest value for the decrease in this ratio is for the ogival nose projectile (15.7%), with up to 45% for the hemispherical nose projectile and 54% for the flat nose projectile. Figure 8 shows the original shape of projectile and the final shape after the impact with the observation of severe erosion for the ogival nose projectile.
Figure 6 Residual velocities to initial velocity ratio with ceramic tile thickness

Figure 7 Residual length/original length ratio with ceramic tile thickness
4.4 Energy
During the impact of the projectile on the ceramic tile, part of the kinetic energy of the projectile is transmitted to the ceramic tile in a form of internal energy, and the ratio of internal energy to kinetic energy varies according to shape of the nose as well as the thickness of the ceramic tile.

4.4.1 (4) mm Ceramic Thickness (Figure 9)
Figure 9 illustrates that the amount of the kinetic energy for the three types of projectiles drops with time, it is noticed that the value of the reduction of the kinetic energy is small and at the same time the absorbed internal energy will be small too.

4.4.2 (7) mm Ceramic Thickness (Figure 10)
There is an a large reduction in the kinetic energy for all projectile types for the 7mm thickness, especially for the ogival nose projectile which loses a part of its kinetic energy due to erosion as well as plastic deformation while the third part is absorbed as internal energy by the target.
4.4.3 (10) mm Ceramic Thickness (Figure 11)
For 10 mm thickness, the amount of the kinetic energy significantly drops especially for the ogival nose projectile with increase in the absorbed internal energy. In Figures 9 and 10, it is noticed that the kinetic energies and internal energies lines do not intersect. This is due to the differences in the values with the projectiles still maintaining the major part of their kinetic energies where just a limited amount of internal energy has been absorbed. But when these lines intersect meaning the projectiles have equal internal and kinetic energies, this happened at 30µs. (See Figure 11).

4.5 Fractured Area Size
The fractured area size (rear face) increases with increasing tile thickness and with varying of projectile nose (Figure 5). The largest diameter of the fractured area is at 10 mm thickness where a large amount of energy goes into fracture and a large size of fractured area is formed by the ogival nose projectile (76mm dia.) followed by flat nose projectile (65mm dia.) and finally by the hemispherical nose projectile, due to a peripheral fracture taking place leading to a decrease in the value of the fractured area size in front of the projectile tip.

Figure 10 Kinetic energy and internal energy for all projectile types with time (7mm thickness)

Figure 11Kinetics energy and internal energy for all projectile types with time (10mm thickness).

Figure 12 Fractured zone sizes with ceramic tile thickness for the three types of projectile
5. CONCLUSION
The main advantage of the present study is the reduction in time during the stages of design and testing. Numerical simulation and modelling is a very efficient tool to be employed in reducing the experimental tests number that required for improving armour, since the cost of these tests are relatively high. Besides, the characteristics of the projectile, history of kinetic energies, impact velocities, geometrical and mechanical properties of the ceramic tiles can be predicted.

From the present numerical results, it can be concluded that the projectile nose plays a important role in determining the residual velocities, and the amount of energy which is absorbed by the ceramic tile, this is because the amount of erosion that projectiles suffer is strongly depends on the projectile head shape as well as determining the size of the conical cracked zone. The thickness of the ceramic plate plays a major and fundamental role in the reduction or loss of the ballistic impact energy. These may include the following factors which can be deduced from the present study:

1. The ogival nose projectile has the least residual velocities and is the most exposed to erosion.

2. With increasing the thickness of ceramic tile from 4mm up to 10mm, the amount of energy absorbed by the ceramic increases.

3. The size of fractured area at the rear face of the ceramic which is induced by the three types of projectile is approximately the same for the 4mm ceramic tile thickness, while varying with the ceramic thickness and with projectile nose.

REFERENCES


