Numerical Simulations of Level 3A Ballistic Impact on Ceramic/Steel Armor

Tarin Vanichayangkuranont¹, Kuntinee Maneeratana¹ and Nuwong Chollacoop²

¹ Department of Mechanical Engineering, Chulalongkorn University, Bangkok 10330, Thailand
Tel: 0-2218-6639, Fax: 0-2252-2889, E-mail: tarinv@yahoo.com and kuntinee.m@chula.ac.th
² National Metal and Materials Technology Center (MTEC), Pathumthani 12120, Thailand
Tel: 0-2564-6500 ext 4700, Fax: 0-2564-6403, E-mail: nuwongc@mtec.or.th

Abstract

This article concerns with the ABAQUS simulation of 9-mm-bullet impacts with initial velocities between 419 – 431 m/s on ceramic/steel armor plates, which complies with the level 3A of the National Institute of Justice (NIJ) standard. In most studies, the impactators are very hard compared to the armor. In reality, the bullets are quite soft and frequently disintegrate upon impacts, making them particularly difficult to model. This preliminary study aims to confirm that the relative strength of the bullet and armor is a major aspect in the ballistic simulations. Without trying to accurately capture the bullet rupture, pragmatic numerical models may be obtained by using hard bullets and armor plates with heightened strengths. That is, the bullet is elastic while the strength of ceramic armor, whose function is to shatter the bullet, is raised by increasing the tensile strength. It can be argued that rough simulations of impacts may be obtained and numerical results of 4 simulations, in which the tensile strength of ceramics are heightened, qualitatively agree with the experimental observations.

Keywords: Ballistic impact, ceramic, steel, ABAQUS

1. Introduction

The National Metal and Materials Technology Center (MTEC) has initiated a project to develop the lightweight hard armor, aiming to improve materials, design and produce hard armor prototypes with local materials [1]. As hard armors comprise of layers of ceramic, steel and polymer plates, the design involves the parameter specification on ceramic tile shape/sizes, thicknesses and arrangements of material layers. Thus, the numerical simulation is used to analyze ballistic impacts on the armors in order to obtain rough guidelines, particularly parameter adjustments for the prototype configuration.

So far, the investigated aspects of ABAQUS finite element simulation were the effects of stress wave propagation from dynamic loads, involving elastic and plastic armor (steel) plate [2] as well as the impact of elastic bullet on an alumina plate which fails by brittle failure criterion [3].

During ballistic impacts between a bullet and armor, the bullet tries to punch through the plate and may disintegrate in the process. This phenomenon involves many complex mechanisms, e.g. large deformation, crack and fracture, of both bullet and armor. Thus, it is extremely difficult to emulate these mechanisms in the simulation and may be beyond a normal package capability. Even though modeling of plastically deformed impactors on relatively low strength armors, like composites plates, are achievable in previous studies, impactors on ceramics, which are much harder, are usually assumed to be rigid or elastic in the simulations [3], [4]. In reality, the bullet materials are quite soft, resulting in very large deformation and shattering of bullets upon impacts. Moreover, it is necessary to specify the contact surfaces of the objects coming into contact. The material failure and subsequent removal of both bullet and armor violates and invalidates this contact specification, preventing meaningful results. That is, the impact simulation of relatively soft impactors on such targets causes substantial problems.

This study aims to show that the relative strength of the bullets and armors is a major aspect in the ballistic simulations. Without trying to accurately capture the rupture mechanism of soft bullets, pragmatic numerical models may be obtained by using hard bullets and armor plates whose resistance to fracture is artificially raised. That is, the bullet is elastic and does not fail while the armor plates can. As the particular armor prototype under consideration consists of only alumina and steel layers, only the fracture resistance of the ceramics, which is used to break down the bullet material integrity, are heightened while the property of steel remains unchanged. In addition, as it is unable to obtain accurate material properties at such high strain rates due to the budget and procedure limitation, the results are not expected to be accurate but may be able to point out certain characteristics of the problems. In short, this approach may be quite imprecise, but if it produces some reasonable results that can be analyzed to extract some useful overview tendency or used as a basis for further model refinements, it is definitely better than none at all.

2. Case Studies

The experiments on alumina ceramics and steel plates are used as the case studies [1]. They were conducted at the certification firing range (Figure 1) in an arsenal on 25-26 August 2005. A single 9-mm-bullet was
fired upon each specimen. The impact falls under the 3A threat-level of the NIJ standard [5], which is also adopted into an equivalent code for the Royal Thai Military.

In all, 4 armor specimens, each made up of an alumina plate in the front and a steel back layer, are tested. The alumina plates are constructed from hexagonal ceramic tiles which are glued together and wrapped up by a dynema cloth before assembling with the back steel plate. The thicknesses of these ceramic tiles are 4 mm, 6 mm, 8 mm and 8 mm respectively for the 4 test cases while all steel plates are always 1.5 mm thick. The velocity of the bullets $V_0$, measured by the sensors after the bullets leave from the barrel (Figure 1, left), ranges from 419 – 431 m/s as summarized in Table 1.

![Figure 1. Standard firing tests](image)

The images of the plate damages after impact are shown in Table 2 while the main result, the ability of the plate to withstand impacts and prevent clean penetration, is summarized in Table 1 under the experiment column. Each specimen showed some localized damages on a single tile while the back steel plates show large bulge which causes petal damages in the single test case that the back steel plate is penetrated.

Table 1. Case studies and main results

<table>
<thead>
<tr>
<th>case</th>
<th>$V_0$ (m/s)</th>
<th>specimens (thickness in mm)</th>
<th>exp.</th>
<th>num.</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>431</td>
<td>ceramic (4) + steel (1.5) plates</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>II</td>
<td>419</td>
<td>ceramic (6) + steel (1.5) plates</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>III</td>
<td>426</td>
<td>ceramic (8) + steel (1.5) plates</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>IV</td>
<td>422</td>
<td>ceramic (8) + steel (1.5) plates</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

✗ The bullet penetrates through the plates.
✓ The bullet does not penetrate through the plates.

3. Numerical Simulations
All finite element simulations are performed using ABAQUS/Explicit [6] due to the high speed, non-linear transient responses in the solutions. An axisymmetric model is used for simulations of a round-shape bullet penetrating layers of ceramics and steel plates, as shown in Figure 2.

A real 9-mm Full Metal Jacketed Round Nose (FMJ RN) bullet is made of an outer copper alloy jacket covering a softer lead core and has the nominal mass of 8.0 g. In the modeling, the bullet is assumed to be one solid cylinder with a round nose with the 4.5-mm radius and has total length of 10 mm such that the model corresponds to commercial bullets in terms of diameter and mass. Meanwhile, the armor plates, which are assumed to be homogeneous in each layer, have the 30-mm diameters.

Table 2. Plate damages after impacts

Due to the anticipated severe deformation at contact, a fine mesh is used at the ceramic region directly beneath the bullet tip while a coarser mesh is used further away to...
reduce computational expense (Figure 2). The bullets are modeled with 46 axisymmetric elements while 1350 elements are used for the steel plates. The ceramic plates use up 5712, 6750 and 9000 elements for the 4, 6 mm and 8-mm-thick specimens, respectively. The time step size $\Delta t$ set as automatic.

The fully restrained boundary condition is applied to the outer edge of the armor plates while the center (left side) of the plate follows axisymmetric boundary condition. In addition, the interaction between the bullet and ceramic plate are defined by the surface-to-surface contact model. Using the kinematic contact method, the bullet nose is assigned to be the master surface while the armor plate is the slave node region.

The elastic part is modeled after the gliding copper [7] with the Young’s modulus $E$ of 115 GPa and the Poisson’s ratio $\nu$ of 0.307. However, the density $\rho$ is changed to ensure that the modeled bullet has the mass of 8.0 g.

The ceramic layer of the armor is made of alumina [4] which has $\rho = 3900$ kg/m$^3$, $E = 350$ GPa and $\nu = 0.22$. The material is assumed to be elastic-perfectly plastic with the compressive yield stress $\sigma_{yc}$ of 2400 MPa. The tensile strength $\sigma_t$ of the ceramics is artificially raised from 360 MPa to 600 MPa.

The Johnson-Cook model is used for the steel plate as it is well suited to model metals that are subjected to high strain rate loadings [8]. The yield stress at non zero strain rate $\sigma$ depends on the strain hardening, strain rate hardening and temperature softening such that

$$\sigma = \left[ A + B \left( \dot{\varepsilon}^{pl} \right)^n \right] \left[ 1 + C \ln \left( \dot{\varepsilon}^{pl} / \dot{\varepsilon}_0 \right) \right] \left( 1 - \frac{T}{T_m} \right),$$

where $\varepsilon^{pl}$ is the equivalent plastic strain, $\dot{\varepsilon}_0$ is the reference strain rate. The parameters $A$, $B$, $C$, $n$ and $m$ are material parameters measured at or below the transition temperature $\theta_{mat}$. The $\dot{\varepsilon}$ is the nondimensional temperature which is equal to 1 when the current temperature $\theta$ is greater than the melting temperature $\theta_{mat}$, 0 when $\theta < \theta_{mat}$, and linearly proportional in-between. The Johnson-Cook shear failure is based on the damage parameter $\omega$

$$\omega = \sum \left( \Delta \varepsilon^{pl} / \varepsilon_0^{pl} \right),$$

where $\Delta \varepsilon^{pl}$ is an increment of the equivalent plastic strain and $\varepsilon_0^{pl}$ is the strain at failure.

$$\varepsilon^{pl} = \left[ d_1 + d_3 \exp \left( \frac{p}{q} \right) \right] \left[ 1 + d_4 \ln \left( \frac{\varepsilon^{pl}}{\varepsilon_0} \right) \right] (1 + d_5 \dot{\varepsilon}),$$

where $p$ is the pressure or mean stress, $q$ is the Mises stress, $d_1 - d_5$ are failure parameters. Failure occurs when the value of $\omega$ exceeds 1.

The parameters values of the steel are adjusted from [8] and [9] such that $\rho = 7870$ kg/m$^3$, $E = 200$ GPa and $\nu = 0.33$. The yield stress and strain hardening parameters are $A = 532$ MPa, $B = 229$ MPa and $n = 0.3024$. It is noted that the values of $A$ and $B$ are reduced as the normal graded steels, with weaker properties, are used in the experiments. The strain rate hardening constants are $C = 0.0114$ and $\dot{\varepsilon}_0 = 5 \times 10^4$ s$^{-1}$. The temperature softening parameters are specific heat capacity $C_p = 452$ J/kgK, inelastic heat fraction $\alpha = 0.9$, coefficient of thermal expansion $\beta = 1.1 \times 10^{-5}$ K$^{-1}$, $m = 1$. $\theta_{mat} = 283$ K and $\theta_{npl} = 1793$ K. The fracture strain constants $d_1 = 0.0705$, $d_2 = 1.732$, $d_3 = -0.54$, $d_4 = -0.015$ and $d_5 = 0$.  

4. Results and Discussions

The qualitative results from the simulations are summarized in Table 1 which shows that the bullet can cleanly penetrate the armor in the first case study with the 4-mm-thick ceramic plate but cannot in the other three, conforming to the experimental results. The ability of the bullet to penetrate the armors or, in a reverse viewpoint, the ability of the plates to resist damages can be judged from the depths of bullet penetration as displayed in Figure 3 which shows the displacements in the $z$ directions (Figure 2) of the bullet tips. It is clear that the bullet in case study I penetrates through the armor while other bullets are repelled backwards.

![Figure 3. The depths of bullet penetration.](image)

Figure 4 shows the contours of von Mises stress on deformed meshes, in which failed elements are deleted, of all test cases at various time instants $t$ during the impact. They exhibits high stresses during the first period after the initial impact at the center of the ceramic plates. The stress values decrease afterwards as elements in the high stress regions fail and are deleted from the grids. Damages at back sides of the ceramics, producing many broken pieces, are more extensive than the front sides which receive the direct impact. These damages clearly affect the metal plates which are layered after the ceramics, causing large deformations in the form of bulging. In addition, the deformation in case study I, which shows the bullet penetration, displayed the petal damage characteristics. Both damage characteristics of steel plates concur with the photos from experiments in Table 2.
In the explicit runs, the amount of artificial strain energy, $AE$, that are generated by the programs in order to prevent unduly high deformation and distortion of elements has to be considered. This artificial energy should be low compared to the total internal energy, $IE$, of the system for reliable results [6]. In these simulations, the ratio of artificial energy over internal energy never exceeds 5% (Figure 5) which is considered satisfactory.

The energy of the systems, namely the internal energy ($IE$), the kinetic energy ($KE$) and total energy ($TE$), during impacts are plotted in Figures 6 for the case studies I to IV, respectively.

Figure 4. The deformation and von Mises stress at time instant $t = 0.01, 0.03, 0.05, 0.07$ and $0.09$ ms.

Figure 5. Ratio of $AE$ over $IE$ during the runs.
Figure 6. Energy plots of the case studies I to IV
From the kinetic energy graphs, the KE of bullets decreases rapidly for the first 0.02 ms, signifying that the bullet velocities are greatly reduced during the initial impacts. The bullet KE of the case I remains high as the bullet penetrates through the armor while bullet KE of other cases drops to near zero values.

From strain and total energy plots, it can be seen that the armors can effectively absorb the impact energy of the bullets. If the bullets do not penetrate, as in cases II to IV, the armors can respectively absorb 98.5, 97.4 and 97.8% of the bullet energy. Meanwhile, only 74.0% of the impact energy is absorbed in the case I in which the bullet penetrates through.

When the energy absorption between the ceramic and steel plates are compared, most of the energy that the armor absorbs are stored in the ceramics, accounting for 73.3, 86.5, 92.0 and 90.8% of the total energy that the armor absorbed from the bullet impacts from cases I to IV respectively. This leaves only 26.8, 13.5, 8.1 and 9.3% of the total strain energy in the steel plates.

5. Conclusions
The simulations use the impact model of 9-mm bullets upon ceramic and steel plates. The results show that ceramic absorbs most of the impact energy from the bullets, accounting for more than 80% of the total energy. The most severe damages to the armor occur at the back sides of the ceramic plates due to the superposition of reflecting stress waves. The Johnson-Cook material model can effectively simulates the damages characteristics of the steel plates. The pragmatic model, employing heightened tensile strengths of ceramics with elastic bullets, enables the results to qualitatively agree with the experimental observations.

Acknowledgments
This research is supported by the National Metal and Materials Technology Center (MTEC), contract no. MT-B-48-CER-07-188-I. Special thanks are due to Dr. K. Sujirote, Dr. D. Atong, Dr. K. Prapakorn, Dr. A. Manonukul, Asso. Prof. Dr. T. Amornmakthai, Asst. Prof. Dr. S. Rimduisit and Maj. Gen. Dr. W. Phlawadana.

References