Energy Absorption Characteristic of Thin Monolithic Q235 Steel Plates Under Oblique Penetrating of Ogive-Nosed Projectiles

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Abstract. In this paper, the energy absorption characteristics of single thin Q235 plates impacted by ogival-nosed projectile obliquity were modeled analytically. We offer an empirical formula involved quasi work, petal dynamic power and petal bending to describe the energy consumption of hardened projectile. The energy dissipation at ballistic limit velocity for projectile was obtained based on the empirical formula. Comparing with the energy value at ballistic limit velocity that fitted by simulation results, the analytic value agrees well with the numerical value that validated by experimental. The results show that the analytical formula can determine the energy absorbed by the thin monolithic Q235 target perforating by ogive-nosed projectile at oblique impact.

1. Introduction
Most of the experimental and theoretical approaches that have been published on penetration mechanics involved normal and oblique perforation as their great importance in military and civil applications. In the present paper oblique penetrating into the thin plate of hardened ogive-nosed projectile were focus on. Goldsmith and Backman\cite{1-2} reviewed much of the published literature on non-ideal impacts of projectiles that involved oblique impact. J. Awerbuch and S. R. Bonder\cite{3} performed several series of experiments investigating the mechanics of oblique perforation with pure aluminum and aluminum alloy plates that perforated by 0.22-in.-caliber lead bullets. The author also provided a modified theoretical model associated with the angle of impact. S. P. Virostek\cite{4} considered the direct force measurements during the oblique penetration of projectiles in low velocity ranging from 45 m/s to 170 m/s through experimental apparatus. I. V. Roisman\cite{5} developed an approximate solution of oblique penetration of a rigid projectile into an elastic-plastic target of finite thickness by considering the irrotational isochoric velocity field of the target. His model successfully predicts the residual velocity, the ballistic limit and the residual angle of projectile in normal and oblique
penetration validated by experimental[6]. A pair of papers were produced by P. K. Gupta. The first paper[7] studied the ballistic performance and energy absorption in thin metallic targets with aluminum that impacted by varies shape nosed projectiles including ogival nosed projectiles. In the second paper[8], the author validated the earlier experimental results[9] using method of numerical simulation to investigate the ballistic performance of monolithic mild steel target plates at oblique impact against 7.62 AP projectiles. Zaid Mohammad[10] with coauthors conducted experiments on thin ductile targets to investigate the energy absorption capacity. Haiyang Wei[11] recently investigated the oblique penetration behavior of ogive-nosed projectile into thick aluminum alloy targets. However, the energy absorbed by plate not given briefly[1-3]. This paper attempt obtaining a simplified formula on energy absorption by plate.

2. Analytical model
The energy absorbed by plate is consist of energy of develop the bulge, the propagation of radial cracks, petal dynamic power and petal bending. According to the experimental, we observed the complex phenomenon at obliquity. Many authors contribute to explore the energy absorption theory of oblique penetration. Now we attempt offer an empirical formula.

When the ogive-nosed projectile comes into contact with the thin target plate, the target plate will produce dishing during penetrating process. The petals formed both on the rear and fore of the plate shown in Figure 1. During the process of penetration, it is assumed that the volume is incompressible. When the petals are formed, the material of the target plate around the cavity comes to yield stress and circumferential stress is the only stress of significance in the crater, which regarded as the three hypotheses of Thomson theory.

![Figure 1](image_url)

**Figure 1.** Schematic of the oblique impact.

The energy of plate plastic deformation both quasi and dynamical work is calculated based on the Thomson theory[12]. As Figure 1 shows, the thickness of the plate is  \( h \), the radial of projectile is  \( r_p \) and the oblique angle is  \( \theta \). The area of projectile tail is  \( A \), then the effective thickness of plate and effective area are  \( h / \cos \theta \) and  \( A / \cos \theta \) respectively. The quasi work becomes
\[ W_q = 2\pi(h / \cos \theta)Y \int_0^b s \ln(s)ds = \frac{1}{2} \pi L^2 (h / \cos \theta)Y \]  
\[ (1) \]

Where \( b \) is the borderline of dishing. \( Y \) is the yield stress. \( L = R_0 \theta_0 + h / 2 \) for simplify. Then the above equation can be written as

\[ W_q = 2\pi(h / \cos \theta)Y \int_0^b s \ln(s)ds = \frac{1}{2 \cos(\theta)} \pi (R_0 \theta_0 + h / 2)^2 hY \]  
\[ (2) \]

The kinetic energy of petals is calculated by the dynamic work produced by projectile. The calculation of kinetic energy of petals based on the work of inertia force, the formulation is derived through the work done by inertia force

\[ W_d = \int Fdb \]  
\[ (3) \]

\[ F = M \frac{d^2b}{dt^2} \sin \alpha + \frac{dM}{dt} \frac{db}{dt} \sin \alpha + M \frac{db}{dt} \frac{d\alpha}{dt} \cos \alpha \]  
\[ (4) \]

Then

\[ W_d = \int (M \frac{d^2b}{dt^2} \sin \alpha + \frac{dM}{dt} \frac{db}{dt} \sin \alpha + M \frac{db}{dt} \frac{d\alpha}{dt} \cos \alpha) \sin \alpha db \]  
\[ (5) \]

Where \( M = \pi \rho bh^2 \), \( \alpha \) is the function of time. Then the dynamical work done are

\[ W_d = 1.028 \pi r_p^2 h \rho \left( \frac{\sqrt{\nu_r}}{L_p} \right)^2 \]  
\[ (6) \]

The energy of Crack Propagation is\[^{[13]}\]

\[ W_c = \frac{2\pi nh}{E} [aYF(n)]^2 \]  
\[ (7) \]

where \( a = \frac{r_p}{\cos \theta} \), then

\[ W_c = \frac{2\pi nh}{E \cos \theta} [r_p YF(n)]^2 \]  
\[ (8) \]
Where \( F(n) = 2/\sqrt{n} \). This energy is small compared to other model of energy. The average energy of crack propagation is about 1.4 J. Thus, we neglect the energy of crack propagation. The energy of the petals bending modified from Xu Shuang-xi\textsuperscript{[14]}

\[
W_b = \sum_{i=1}^{n} \frac{k_i h_i^2}{4} Y \phi_i
\]

(9)

Where \( n \) is the total number of petals. The total energy is

\[
E = W_q + W_d + W_b
\]

(10)

\( E \) is the energy absorbed by plate. When \( v_r = 0 \), the ballistic limit velocity can be calculated from empirical formula as follow

\[
v_{50} = \sqrt{\frac{2(W_q + W_d + W_b)}{m_p}}
\]

(11)

3. Numerical modelling

3.1. Finite element modelling

The numerical simulations were performed using commercial software LS-DYNA. It has been demonstrated that using Lagrange finite element technique for the dynamic loading processes at high-speed events could provide reliable predictions.

Based on the phenomena observed in the above experiment, mirror-symmetric impact causes non-mirror-symmetric deformation and failure of target, which is beyond the prediction capability of a symmetric finite element model. Hence, a three-dimensional (3D) full finite element model was employed to build the projectile and targets.

The model consists of the square target plate and the cylindrically shaped projectile with ogive nose shape. Initially, a 0.5 mm gap space between the projectile and the target was specified. The FEM of target plate, presented in Figure 2, was in-plane simplified dimensions of 160 mm×160 mm and a thickness of 4.6 mm. The dimensions of finite element model for projectile were the same as real projectile. Figure 2 shows the finite element model of the projectile and target, which were meshed by Lagrange eight-node solid element with full integration. The target was divided into two zones for different mesh densities in order to maintain numerical accuracy by assigning finer mesh size at the impact area and save the computational efficiency. Intensive meshed zone was considered to 60 mm×60 mm square and based on convergence study it was meshed with element size 0.2 mm\(^3\) whereas around the finer meshed zone was meshed with coarser mesh to reduce the computational time [reference]. More detail information about mesh is shown in Figure 2. The constraint of the target is shown in Figure 3.
The dynamic erosion contact technique (contact eroding surface to surface) is used to achieve the interaction of projectile and target plate. The element deletion technique is introduced to simulate the potential crack initiation and propagation. When the damage of an element exceeds the critical value, all the components of stress in that element are reset to 0, the material fails, and the element is deleted. It must be pointed out that the element deletion technique is just a feasible approach to realize material separation and it suffers from mass, momentum and energy loss, etc. To reduce the influence of element elimination on the impact, elements in the possible fracture region should be controlled to a sufficient small size within an allowable computational expense. The initial load is the projectile impact velocity. The general contact algorithm available in LS-DYNA with no friction between the contacting parts was used in the calculation.

3.2. Strength and fracture model

Up to now, Johnson-Cook proposed the constitutive model that is able to characterize metal materials well undergoing large strains, high strain rates and high temperatures\textsuperscript{[15]},

$$\sigma = (A + B\varepsilon^{*})(1 + C \ln \dot{\varepsilon}^{*})[1 - (T^{*})^{n}], T^{*} = \frac{T - T_{R}}{T_{m} - T_{R}}$$ (12)

Where $\sigma$ is von Mises flow stress in the left of equation, $\varepsilon^{*}$ is the equivalent plastic strain, $\dot{\varepsilon}^{*}$ is the dimensionless plastic strain rate, $T_{R}$ and $T_{m}$ are the room temperature and material melting point, respectively. $A$, $B$, $n$, $C$ and $m$ are material constants determined on the basis of experimental data.

The form of the Johnson and Cook accumulating damage fracture model\textsuperscript{[16]} is defined as
\[
D = \sum \frac{\Delta \vec{\varepsilon}}{\varepsilon'}
\]  

(13)

Where \( \Delta \vec{\varepsilon} \) is the increment of equivalent plastic strain during a single iteration, and \( \varepsilon' \) is the equivalent strain to failure under the current conditions of strain rate, temperature and stress triaxiality. Failure is then allowed to occur when \( D=1.0 \) of an element. The expression of \( \varepsilon' \) is given by

\[
\varepsilon' = [D_1 + D_2 \exp(D_3 \sigma^*)][1 + D_4 \ln \dot{\varepsilon}^*][1 + D_5 T^*]
\]  

(14)

Where \( D_i \) \((i=1, \ldots, 5)\) are the material parameters, and \( \sigma^* \) is stress triaxiality. The dimensionless strain rate \( \dot{\varepsilon}^* \) and homologous temperature \( T^* \) are the same as equation of strength model.

Many people have investigated constitutive of steel and given a series of parameters of Johnson and Cook constitutive model on Q235(A3) steels. Chen X W\cite{17} roughly presented a series of parameters of Q235 steel Y F Deng and Xiao Xinke\cite{18} provided the parameters about Q235 based on experiments. The parameters of Johnson and Cook constitutive and Johnson and Cook damage accumulative model for Q235 target are show in Table 1.

| Table 1. Johnson-Cook material parameters for Q235 steel\cite{18}. |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|
| \( \rho \) (gcm\(^{-3}\)) | \( E \) (GPa) | \( \mu \) | \( C_p \) | \( \eta \) | \( T_r \) (K) | \( T_m \) (K) | \( \dot{\varepsilon}_0 \) (s\(^{-1}\)) | \( A \) (MPa) |
| 7.8 | 200 | 0.33 | 469 | 1 | 293 | 1795 | 1.1×10\(^{-3}\) | 229.0 |

| \( B \) (MPa) | \( n \) | \( c \) | \( m \) | \( D_1 \) | \( D_2 \) | \( D_3 \) | \( D_4 \) | \( D_5 \) |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|
| 439.0 | 0.503 | 0.10 | 0.55 | 0.30 | 0.90 | -2.8 | 0.0 | 0.0 |

The material model of hardened projectile is plastic kinematic in LS-DYNA material database. The material properties for projectile were incorporated from T Borvik\cite{19}. All parameters for projectile have been mentioned in Table 2.

| Table 2. Plastic kinematic material parameters for projectile\cite{19}. |
|-------------|-----|-----|-----|-----|
| \( \rho \) (gcm\(^{-3}\)) | \( E \) (GPa) | \( \mu \) | \( \sigma_y \) (MPa) | \( E_t \) (MPa) |
| 7.85 | 204 | 0.33 | 1900 | 15000 |

4. Results and discussion

4.1. Results of simulation and experimental

Using the numerical model stated above, the simulations were carried out for a wide range of impact velocities varying from 180 m/s to 672 m/s. Experimental conducted impact cases at velocities ranging
from about 490 m/s to 672 m/s as well. Experimental results and corresponding numerical results of the response of all targets are presented in Figure 4 to Figure 11. These data are the measured from experimental and simulation. Comparing to the results of experimental and simulations, the simulation results agree well with the experimental data.

Figure 4 shows the cross sections of Q235 plates with different projectile velocities. As the velocity increase, the angle of primary and the angle of secondary remain unchanged observed in experimental. The definition of primary and secondary angle is shown in Figure 6. The radius of penetration hole is approximate. It revealed that the energy absorbed by ductile enlarge the hole is close to the same value. The plate deformation consists of a combination of localized ductile involved the ductile of enlarge the hole, global dishing and the bending of the petal. This deformation consumed the majority energy of projectile lose. It exactly in line with the empirical formula described. This energy calculated reached approximately to 80% of total energy.

The else energy absorbed though the crack propagation and the petal velocity. The petal velocity will not suffer a significant change unless the petal departs from the plate.

The bending distance was used to describe the global dishing of the plates after penetration as shown in Figure 9. The distance decreases as the velocity increase. This indicate that more energy will be absorbed by plate through global dishing in low velocity.

Numerical simulations can be calibrated and verified through these ballistic penetration tests on Q235 steel plates impacted by hardened ogive-nosed projectiles at ordnance velocities.

Figure 4. Cross sections of Q235 plates with different projectile velocities.
Figure 5. Petals formed both rear and fore of plate in experimental and simulation.

Figure 6. Schematic of primary angle and secondary angle.

Figure 7. Primary angle vs. initial velocity.

Figure 8. Secondary angle vs. initial velocity.

Figure 9. Bending distance varying velocity.
Figure 10. Initial velocity vs. residual velocity

4.2. Energy absorbed at ballistic limit velocity

The ballistic limit velocity calculated using Recht-Ipson\cite{20} empirical model,

\[ v_r = a(v_i^p - v_{50}^p)^{\frac{1}{p}} \]  

(15)

Where \( v_r, v_i \) and \( v_{50} \) is initial, residual and ballistic limit velocity, \( a \) and \( p \) are the constants parameters. The nonlinear least square method was used to determine the parameters \( a, p \) and \( v_{50} \) as 1.02, 1.677 and 188.8, respectively.

Figure 11. Initial velocity vs. residual velocity.

Figure 12. Energy absorbed by plate.
As shown is Figure 12, the result of empirical formula agrees well with the value of simulation. The ballistic limit velocity is 192 m/s. The value difference between simulation and empirical formula is 3.2 m/s.

The energy plate absorbed in simulation is great than the energy calculated by empirical formula. The most important reason is that we neglect the energy of crack propagation. As velocity increase, the value becomes close. It reveals that the empirical formula more suitable for high velocity.

5. Conclusion
The present study investigated the energy absorption characteristics of the thin Q235 plate oblique impact by ogive-nosed projectile. The initial and residual velocities of projectile observed in experiments and simulations have been depicted in Figure 4 to Figure 11. The ballistic limit velocity was calculated in numerical simulations as well as empirical formula. Further the ballistic limit value obtained from the numerical simulation were compared with analytic value from the empirical formula, and the value was found approximately close to each other. This validates the correction of the empirical formula in ogive-nosed projectile oblique perforating the thin metallic plate.

6. References
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