Defence Science Journal, Vol 48, No 3, July 1998, pp. 271-276

Ballistic Behaviour of Thick Steel Armour Plate under Oblique Impact: Experimental Investigation

S. N. Dikshit
Defence Metallurgical Research Laboratory, Hyderabad - 500 058.

ABSTRACT

The ballistic behaviour of thick steel armour plate has been investigated at different obliquity when impacted by an ogive-shaped steel projectile. The ballistic experiments have been conducted in the velocity range 300-800 m/s. Both the thickness of the target plate and the diameter of the projectile were 20 mm. At 30 and 45° obliquity 20 mm plate provides full protection at 800 m/s, whereas at 0 and 15° obliquity, the plate provides protection up to 600 m/s. At 15 and 30° obliquity, the plate exhibits lesser energy absorption capacity due to higher crater volume.

1. INTRODUCTION

Many investigators have conducted extensive experimental and theoretical studies for understanding the projectile-target interaction at normal impact angle, i.e., at zero obliquity. In contrast, projectile-target interaction studies involving oblique impact are restrictive in nature. These restrictions emerge mainly due to two reasons. Firstly, complexity of the oblique impact impose restrictions in making simplified assumptions in analytical as well as experimental methods. Secondly, the research in the oblique impact situations finds direct applications in the design of military vehicles and systems, due to lesser weight penalties. Indeed, the subject of oblique impact assumes significance under the condition of ricochet in oblique attack at the target plate, wherein, changes in the direction, the velocity and the rotational motion of the projectile take place due to several mechanisms[1]. During the last two decades, the penetration and ricochet studies on thin metallic and composite armour involved impact by hard ball[2-3], long rod penetrators and small arms ammunition. However, the penetration and ricochet studies at subordnance velocities, involving impact of moderately thick steel armour plate (plate thickness equal to projectile diameter) have received less attention.

In view of the importance of obliquity in enhancing the protection of armoured fighting vehicles, there is a need to develop an understanding of the projectile-target interactions in steel armour plates at different obliquity. The objective of the present investigation is to study the ballistic behaviour of thick steel armour plate at subordnance velocities when impacted by an ogive-shaped steel projectile and illustrate its dependence on the impact velocity, the crater volume (U) and the angle of impact. Here, obliquity refers to the angle of attack, impact angle and angle of incidence, wherein zero obliquity corresponds to an impact angle of 0°.

2. EXPERIMENTAL DETAILS

The rolled homogeneous armour (RHA) plates of 20 mm thickness and having hardness of

Received 14 May 1997, revised 04 December 1997

HV-350 ± 10 were used as target plates. A steel cylinder with ogive nose, of diameter 20. mm, having hardness of Hv 600 ± 10 was used as projectile. Mass and length-to-diameter ratio of the projecitle was 110 g and 5.73, respectively. The sizes of the plates used were 450 x 450 x 20 mm^3 Ballistic tests were conducted in the velocity range 300-800 m/s, at 0, 15, 30 and 45°. Detailed procedure followed for ballistic trials is mentioned in the literature[4]. During the test, the steel armour plates were firmly clamped to the target holder, though earlier work[15] had clearly indicated that the clamping force does not influence the ballistic performance in the velocity range used in this investigation in normal angle of attack. Depth of penetration (*Xp*) and crater volume (*U*) were measured as described elsewher[4].

3. EXPERIMENTAL RESULTS

3.1 Appearance of Impacted Plates

The impacted steel armour plates of 20 mm thickness were examined for assessing the nature and mode of deformation of the plate material during projectile penetration. Bulge was noticed on 20 mm plate impacted by 20 mm diameter projectile at 0, 15 and 30° obliquity. Bulge details are provided in Table 1 and Fig. 1. Provides photographs of some select craters at different obliquity.

3.2 Penetration Depth

The depth up to which the projectile penetrated into steel armour plates of 20 mm thickness at different obliquity and velocities were experimentally measured (Fig. 2). It is observed from Fig. 2. that *Xp* increases monotonically with striking velocity of the projectile. It is also noticed that with increasing obliquity there is a decrease in the slope of the penetration curves. This kind of plate behaviour indicates a decreasing penetration severity with increasing angle of attack, which is well within the ballistic expectations. The ballistic behaviour of 20 mm plate on being impacted by 20 mm diameter steel projectile at different velocities (V= 300-600 m/s) is identical to 0 and 15° obliquity. However, plate behaviour is observed to be quite different at 30° obliquity though it is similar to the one noticed at 45° obliquity.

3.3 Crater Volume

The variation of U with the striking velocity (V) of a 20 mm diameter steel projectile when impacted on a 20 mm thick steel armour plate is presented in Fig. 3. Crater volume at 45° obliquity is observed to be the least at all velocities in comparison to 0, 15 and 30° obliquity. An interesting observation is that U at 30° obliquity is maximum in the low velocity regime (V = 300-550 m/s). Crater volume at 0 and 15° obliquity is almost the same and it is expected to be so as X_p noticed in Fig. 2 at 0 and 15° obliquity is quite close to each other.

3.4 Energy Absorption Capacity

The cummulative specific energy (E_{sc}) absorbed by the steel armour plate during the projectile penetration is given by:

$$E_{sc} = 0.5\ mV^2/U \qquad (1)$$

Where m is the mass of the projectile, V is the striking velocity of the projectile at the time of impacting the target on its front-face and U is the volume of the crater that is formed in the target by the impacting projectile. The E_{sc} has the unit of strength (MPa) or equivalently, energy per unit volume (J/m^3) and represents the average resistance offered by the plate. In the present investigation, it is assumed that Eqn (1) also holds good at angles other than the zero angle of attack.

The variation of E_{sc} in 20 mm thick steel armour plate with striking velocity of the projectile at different obliquities is provided in Fig. 4. The energy absorption capacity of the plate increases with increasing velocity both at 30 and 45° obliquity. In contrast, at 0 and 15° obliquity, plate resistance decreases with the increasing striking velocity. The decrease in plate resistance at higher velocities is predominent at 0° than at 15°. Plate offers more resistance to obliquity penetration at 45° than that at 30° (at all velocities). In fact,

Table. 1. Details of the bulge

Obliquity (θ°)	Bulge Observations
0	(a) No bulge at 300 m/s (b) Severe bulge at all velocities > 300 m/s
15	(a) No bulge at low velocity (b) Bulge noticed at higher velocity (V > 450 m/s)
30	(a) No bulge up to 630 m/s
45	(a) No bulge up to 700 m/s (b) Smooth bulge at the highest velocity (V = 800 m/s)
Diameter of the projectile	20 mm
Thickness of the target plate	20 mm
Hardness of the projectile	Hv 600 ± 10
Hardness of the plate	Hv 350 ± 10

resistance offered by the plate at 15 and 30°obliquity is smaller than that at 0°, which is contrary to the basic understanding of the mechanism of penetration.

4. DISCUSSIONS

4.1 Obliquity & Penetration

Data presented in Fig. 2 clearly shows that the penetration behaviour with increasing velocity at 30 and 45° obliquity is quite different than that noticed at 0 and 15° obliquity. This kind of change in ballistic behaviour of armour plate is basically related to the ricochet angle (θ_r) of the projectile used in the present investigation. The ricochet angle of 20 mm ogive-shaped steel projectile[6] used here is about 30 to 35°. However, as expected, at a given velocity, X_p is observed to decrease with increasing obliquity. Ballistic behaviour of 20 mm steel armour plate can be understood better by plotting X_p with obliquity. Figure 5 provides variation of X_p with the obliquity of the projectile with the plate target. Depth of penetration is maximum at 0° obliquity and minimum at 45° obliquity, and also, penetration increases with increasing velocity. Such a behaviour of the plate is also evident from Fig. 2. It is observed that reduction in X_p from 0 to 15° of incidence is not severe in nature and similarly, reduction in X_p from 15 to 30° angle of incidence is also quite nominal. However, reduction in X_p from 15 to 30° angle of incidence is severe in nature and careful examination of the data presented in Fig. 5 reveals that the maximum reduction in X_p takes place at an obliquity of about 30° to 35°. Angle of incidence at which maximum reduction took place in X_p is actually θ_r of the projectile at which, the projectile leaves the target plate after partial penetration (grazing) of the target.

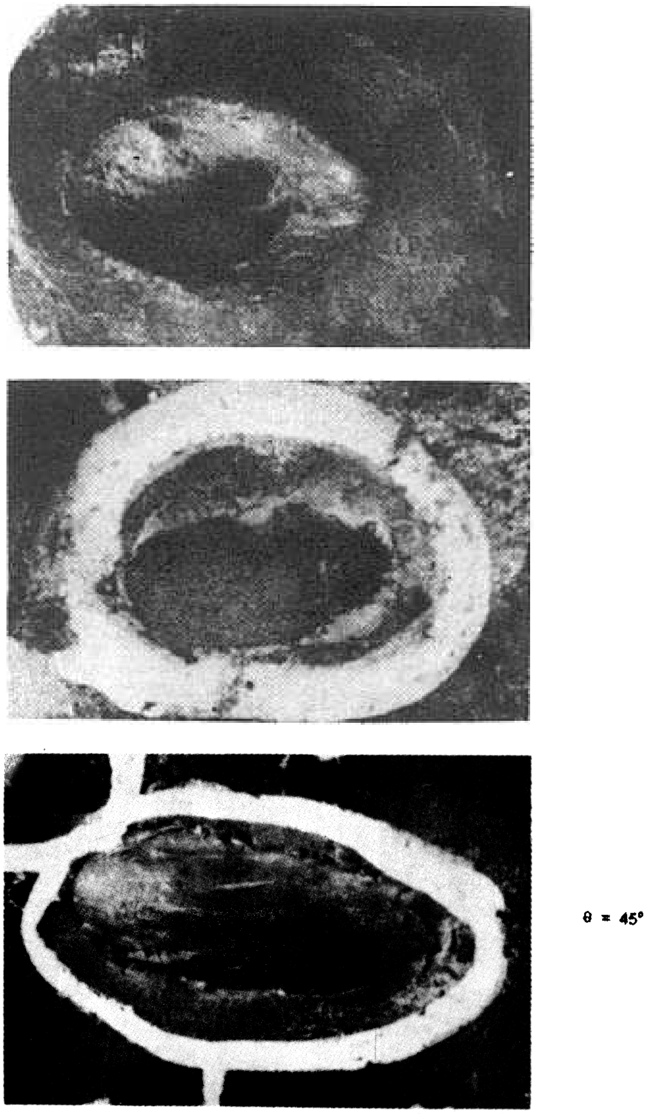

Figure 1. Typical appearance of crater formed by the impact of 20 mm ogive-shaped steel projectile on 20 mm steel target plate at different obliquity (θ°).

4.2 Obliquity & Cummulative Specific Energy

The specific energy absorbed by the plate with striking velocity of the projectile was presented in

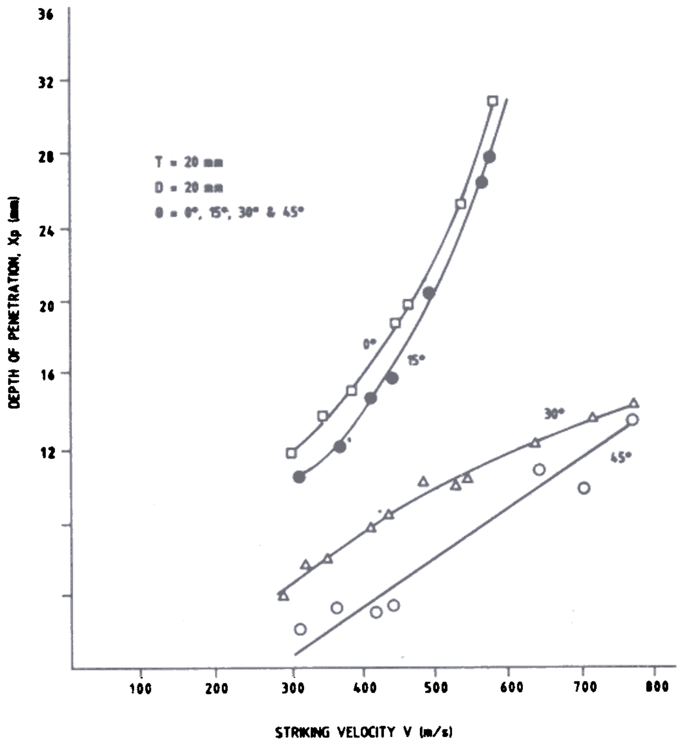

Figure 2. Variation of depth of penetration with velocity of projectile at different obliquity (θ^o).

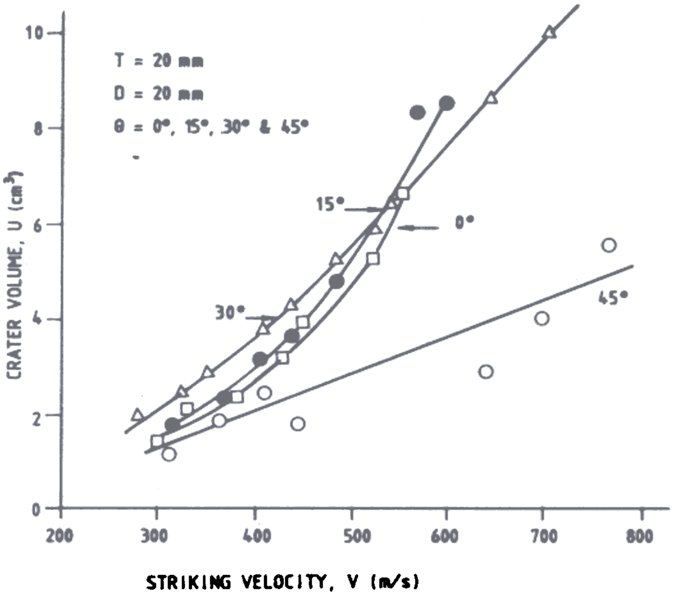

Figure 3. Variation of crater volume with velocity of projectile at different obliquity (θ^o).

Fig. 4. This data if plotted as E_{sc} with plate obliquity can be understood better as shown in Fig. 6. It is observed that plate offers more resistance to the penetrating projectile at zero obliquity in comparison to 15 and 30° obliquity. Also, at 0, 15 and 30°obliquity, plate resistance decreases with the increasing striking velocity of the projectile. This kind of ballistic behaviour of plate is in agreement with the mechanism of ballistic penetration of armour plates. The plate offers maximum resistance to penetration at 45° obliquity and the same is also evident from Fig 2. Increasing specific energy absorption capacity of the target plate at high obliquity ($\theta_r > 30^o$) is related to θ_r of the projectile. It is also evident from Fig. 6 that the plate offers more resistance to penetration at higher striking velocities of the projectile than that at the lower striking velocity at 45° obliquity. Such a behaviour of plate is opposite to the one noticed at 0° obliquity in Fig. 6. This kind of reversal in the ballistic behaviour of plate at 0 and 45° obliquity is related to θ_r of the projectile. It is clear from Fig. 6 that the concept of cummulative specific energy absorbed by the plate holds good so far as the angle

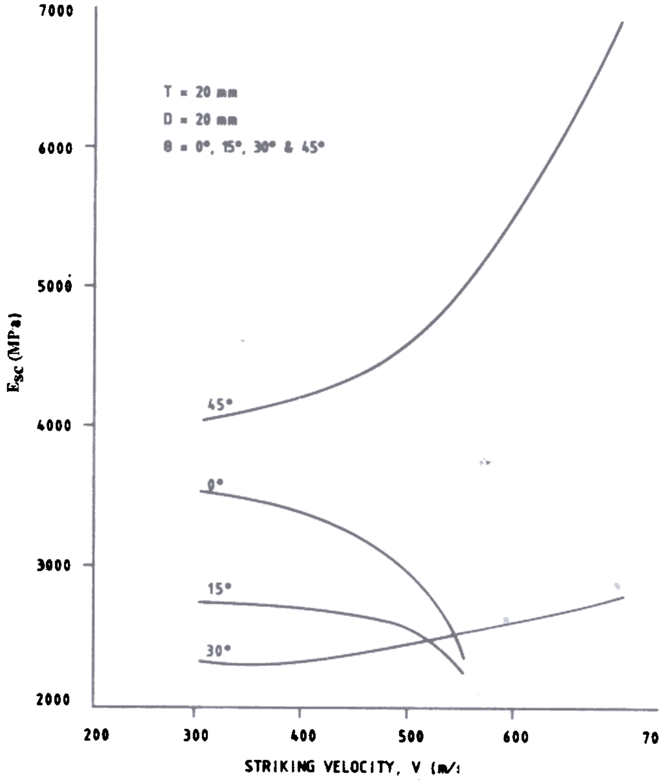

Figure 4. Variation of E_{SC} with projectile velocity at different obliquity (θ^o).

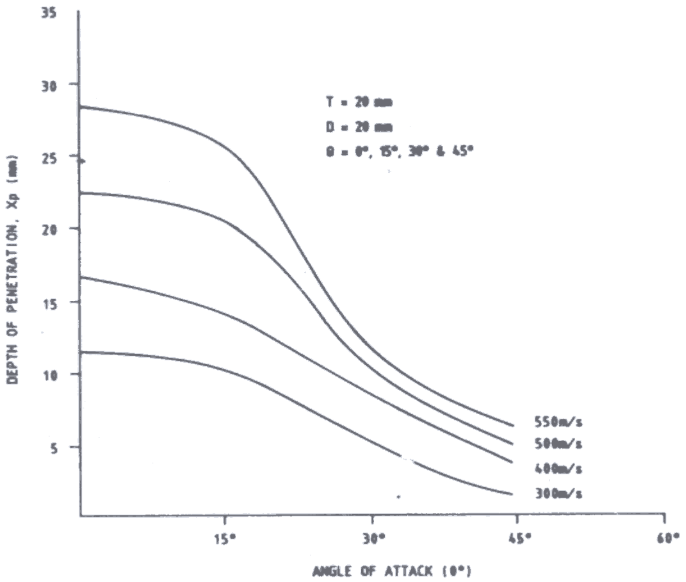

Figure 5. Variation of depth of penetration with obliquity (θ°) at different velocities.

of attack (obliquity) is less than θ_r of the projectile target combination. If obliquity is more than θ_r, energy imparted to the plate is very small due to projectile ricochet, wherein frictional energy is quite significant and its estimate can be made by knowing the residual velocity of the projectile. However, the residual velocity could not be measured due to the experimental difficulties.

4.3 Crater Volume at 15 & 30° Obliquity

It was noticed above that the average resistance offered by the plate at 15 and 30° obliquity was lower than that offered at 0° obliquity. The decrease in resistance to penetration is mainly due to increase in *U*, as the plate resistance is inversely proportional to *U*.

The increase in *U* at 15 and 30° obliquity observed in this investigation may either be related to the texture or to the size and shape of the projectile. Further investigation is needed to understand this kind of plate behaviour.

5. CONCLUSIONS

(a) Depth of penetration decreases with increasing obliquity of the target plate.

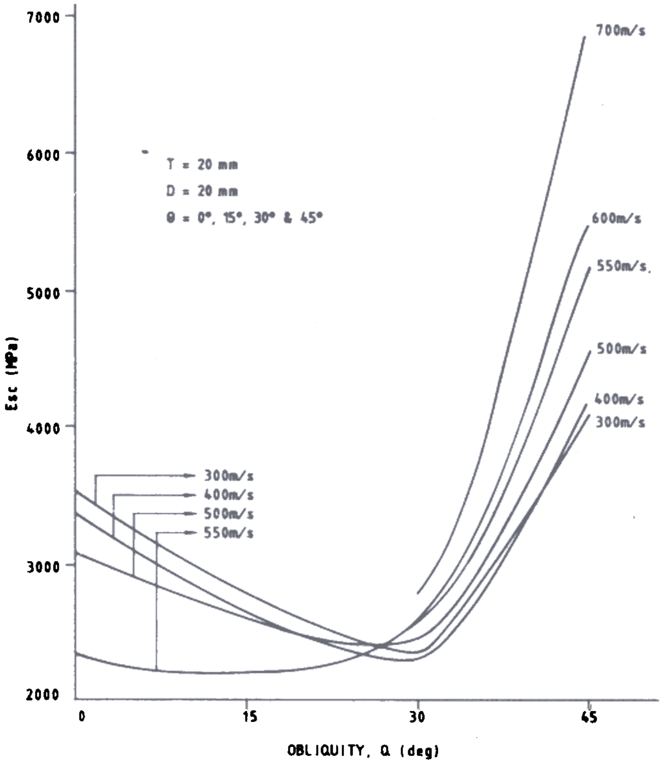

Figure 6. Variation of E_{SC} with obliquity (θ°) at different velocities.

(b) Armour plate inclined up to 15° does not offer substantial weight reduction, as reduction in X_p at 15° obliquity is very small in comparison to the 0° inclination.

(c) Average resistance offered by the plate decreases with increasing velocity as far as the plate obliquity (θ) is less then θ_r i.e., $(\theta < \theta_r)$.

(d) Ballistic behaviour of plate drastically changes at an obliquity greater than the ricochet angle of the projectile i.e., $(\theta > \theta_r)$

(e) The 20 mm plate when impacted by 20 mm ogive-shaped steel projectile provides full protection even up to 800 m/s at higher obliquity (θ = 30 - 45°), whereas at lower obliquity (θ = 0 - 15°), plate provides protection only up to *V* of 600 m/s.

(f) Plate exhibits lesser energy absorption capacity at 30° obliquity due to higher *U*

ACKNOWLEDGEMENT

Author wishes to express his gratitudes to Dr Dipankar Banerjee, Director, Defence Metallurgical Research Laboratory (DMRL) for granting permission to publish this paper. Author also wishes to express sincere thanks to Dr P. Rama Rao, Chairman, Atomic Energy Regulatory Board, Government of India and former Director, DMRl for his constant encouragement.

1. Zukas, J.A. & Gaskill, B. Ricochet of deforming projectile from deforming plates. *Int. J. Impact Engg.*, 1996, **18** (6), 601-10.
2. Sundararajan, G. Energy absorbed during the oblique impact of a hard ball against ductile, semiinfinite target materials. *Int. J. Impact Engg.*, 1990, **9** (3), 343-58.
3. Hutching, I.M.; Macmillan, N.H. & Rickerby, D.B. Further studies of the oblique impact of a hard sphere against a ductile solid. *Int. J. Mech. Sci.*, 1981, **23**, 639.
4. Dikshit, S.N. & Sundararajan, G. The penetration of thick steel plates by ogive-shaped projectiles. Experiment and analysis. *Int. J. of Impact Engg.*, 1992, **12** (13), 373-408.
5. Dikshit, S.N. & Sundararajan, G. The effect of clampings rigidity of the armour on ballistic performance. *Def. Sci. J.*, 1993, **42** (2), 117-20.
6. Dikshit, S.N. & Sundararajan, G. Behaviour of a kinetic energy projectile on angular impact. *Def. Sci. J.*, 1998, **38** (3), 293-99.

Contributor

Col (Dr) SN Dikshit, VSM, obtained his BE (Metallurgy) from RECW, ME (Mechanical) from Indian Institute of Science, Bangalore and PhD from Banaras Hindu University, Varanasi, in 1970, 1982 and 1994, respectively. At DMRL, he is actively engaged in the design and development of light weight *Kanchan* composite armour and 'explosive reactive armour' for the protection of main battle tanks *Arjun, Vijayanta* and *Ajeya*. He has published several papers in international and national journals. He is a life member of the Indian Institute of Metals. He was awarded *Vishisht Seva Medal* for his meritorious services in the field of armour in 1997.