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Research Paper

Impact Response of Single and Layered Thin Plates

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This paper concludes some of the important observations made by the authors during their recent experimental and numerical studies based on the response of thin aluminum plates subjected to projectile impact. The influence of plate thickness, configuration, projectile shape and angle of incidence has been studied in detail leading to some important findings which have not been identified earlier. The monolithic target has been found to be superior to stop the projectile compared to that of the layers placed in contact with equivalent thickness. The layers with in-between spacing have been found to be most inferior target configuration. The angle of incidence has been found to influence the target resistance particularly at high obliquity. At very high obliquity the projectile has ricocheted from the target surface with or without tearing the target. The angle of ricochet has been found to be the function of projectile velocity, nose shape and target thickness.

Key Words : Finite Element Modelling; Projectile Shape; Target Configuration; Angle of Incidence; Ballistic Resistance; Single and Layered Thin Plates

1. Introduction

The mechanics of deformation and fracture behaviour of metallic plates subjected to projectile impact has been significantly studied in the literature in order to understand the ballistic response of armor, aircraft and other vulnerable structures. Thin aluminum plates have been found to absorb significant energy undergoing plastic deformation. These plates are significantly used in automobiles and aircraft industries. In addition, they have also been found to possess excellent ballistic capabilities. However, the ballistic investigation of these plates is highly complex due to the interdependence of various mechanical phenomena occurring simultaneously such as high rate of deformation, temperature softening, damage and fracture. In spite of this the ballistic response of such plates has been significantly studied in literature. Experiments carried out with thin aluminum target impacted by blunt, conical [13, 15-16] as well as hemispherical projectiles [17, 18] revealed that monolithic target is more efficient to stop the projectile than layered in contact plates of equivalent thickness. Arias *et al.* [13] investigated the perforation behaviour of thin steel plates impacted by blunt, conical and hemispherical nosed projectiles with a large range of impact velocities, 190 to 600 m/s. The failure of a target against blunt projectile occurred due to adiabatic shearing and plugging, while conical projectiles failed the target by hole enlargement and hemispherical projectile by thinning and stretching of material. Johnson *et al.* [14] investigated the ballistic performance of aluminum and steel layered plate structure. The metallic structure was made monolithic, double and triple-layered of either steel or aluminum or a combination of these materials and hit by a 7.62 mm APM2 projectile. The ballistic limits of monolithic plates were found higher than that of multi-layered

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plates of same material. It was also found that double-layered plates with a thin front plate of aluminum and thick back steel plate have greater resistance than layered steel plates with similar areal density. Borvik *et al.* [19] performed numerical simulations to investigate the impact response of thin plate using the non-linear finite element code LS-DYNA. It was concluded that in case of blunt projectiles the ballistic limit velocity decreases for increasing strength, while the opposite trend was found for conical and ogival projectiles. To investigate the oblique effect on ballistic resistance Gupta and Madhu [21] performed some experiments on single and layered plates of mild steel, RHA steel and aluminium subjected to the normal and oblique impact of armour-piercing projectiles within 800-880 m s^{-1} velocity regime. The effect of plate thickness and ratio of the plate thickness to the diameter of the projectile for single plates as well as for layered plate on ballistic resistance were studied. The target thickness for which the incident velocity became the ballistic limit was determined and expression for residual velocities was developed.

In the present paper, some of the recent experimental and numerical studies carried out by the authors have been summarized pertaining to the ballistic response of thin aluminum plates. The observations made by the authors are related to the response of these plates to projectile shape, target configuration, angle of incidence, target thickness. A large number of experiments and numerical simulations were carried out in order to conclude these findings. The experiments were conducted using a pneumatic gun capable to launch small projectile in the sub-ordinance velocity range. The numerical simulations were carried out using ABAQUS/Explicit finite element code. The axi-symmetric as well as 3-dimensional numerical simulations were performed and the results thus obtained were compared. The numerical simulations led to few important findings such as projectile ricochet and the parameters influencing the critical angle of ricochet, which otherwise would have been very difficult to be determined through experimentation.

2. Finite Element Modelling

The finite element analysis was based on the assumption of rigid projectile and deformable target. The assumption is justified since the strength of the aluminum plates was significantly low in comparison to that of the steel projectile. The contact between the projectile and target was assigned using Kinematic as well as Penalty contact algorithm however, as such no difference in the numerical results was observed. The contact between the contacting surfaces of layered in contact target was assigned using General contact algorithm. It was observed that friction between the projectile and target does not play a significant role for thin targets therefore the effect of friction between the projectile and target was considered negligible. However, a coefficient of friction 0.5 was assigned between the contacting surfaces of layered target. The outer surface of the projectile was modelled as the master surface and the contact region of the target as node based slave surface. The rear surface of front layer was considered as master surface and front surface of rear layer was considered as the slave surface. 8-node brick elements were considered for meshing the target plate. Dynamic explicit method was used to solve the impact phenomenon.

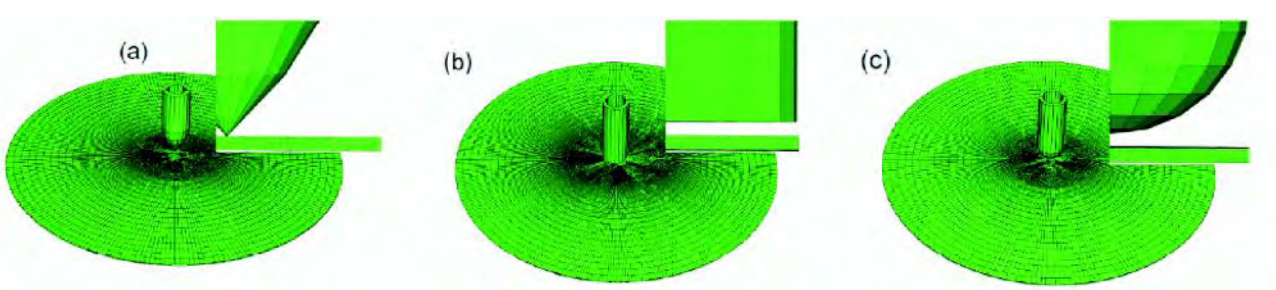

Fig. 1: Finite element model; (a) ogive nosed projectile case; (b) blunt nosed projectile case; (c) spherical nosed projectile case

To study the convergence the elements over target thickness were varied as 3, 4, 5, 6 and 7 and the target was impacted at each mesh configuration by ogive nosed projectile at a constant velocity of 64.46 m/s. For 1 mm monolithic target element size for aspect ratio 1 were 0.33 x 0.33 x 0.33 mm^3, 0.25 x 0.25 x 0.25 mm^3, 0.16 x 0.16 x 0.16 mm^3 and 0.14 x 0.14 x 0.14 mm^3 corresponding to 3, 4, 5, 6 and 7 elements respectively. The corresponding residual velocity of projectile was found to be 17.92 m/s, 28.14 m/s, 29.4 m/s, 32.19 m/s and 32.41 m/s corresponding to 3, 4, 5, 6 and 7 elements respectively. Up to element size 0.20 x 0.20 x 0.20 mm^3 the velocity drop of projectile decreased and then it became almost constant. It was concluded to mesh the monolithic target with element size 0.16 x 0.16 x 0.16 mm^3 in impact region. The total number of elements was 199178, in the whole model.

3. Material Modelling

The simulations of a metal plate subjected to projectile impact is a very complex phenomenon due to involvement of yielding, plastic flow, isotropic strain hardening, strain rate hardening, softening due to adiabatic heating and damage. Johnson-Cook elasto-viscoplastic constitutive model [1, 2] that considers all the above effect of linear thermo-elasticity, is used to simulate the material behaviour of 1100-H12 aluminum.

The equivalent von-Mises stress for the Johnson-Cook model is expressed in the following form;

$$\bar{\sigma} = [A + B(\bar{\varepsilon}^{pl})^n][1 + C\ln\left\{\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\bar{\varepsilon}}_0}\right\}][1 - \hat{T}^m] \quad (1)$$

while the failure strain is expressed by;

$$\bar{\varepsilon}^{pl}\left(\frac{\sigma_m}{\bar{\sigma}}, \dot{\bar{\varepsilon}}^{pl}, \hat{T}\right) = \left[D_1 + D_2 \exp\left(D_3 \frac{\sigma_m}{\bar{\sigma}}\right)\right]$$

$$\left[1 + D_4 \ln\left(\frac{\dot{\bar{\varepsilon}}^{pl}}{\dot{\varepsilon}_0}\right)\right][1 + D_5\hat{T}] \quad (2)$$

$$\hat{T} = (T - T_0)/(T_M - T_0) \quad (3)$$

where T is the current temperature, T_M is the melting temperature, T_0 is the room temperature, A is quasi-static yield stress, B is a hardening constant, n is the hardening exponent, C is the strain rate sensitivity parameter and m is the temperature sensitivity parameter. $\bar{\varepsilon}^{pl}$ is the equivalent plastic strain, $\dot{\bar{\varepsilon}}^{pl}$ is equivalent plastic strain rate, $\dot{\bar{\varepsilon}}_0$ is a reference strain rate, D_1-D_5 are material parameters, $\frac{\sigma_m}{\bar{\sigma}}$ is the stress tri-axiality ratio and σ_m is the mean stress. The different material parameters for Aluminum 1100-H12 of Johnson Cook constitutive model as well as Johnson Cook fracture model are shown in Table 1.

4. Results and Discussion

The paper concludes some of the important observations made by authors during their recent studies conducted on thin aluminum plates subjected

Table 1: Material parameters for 1100-H12 aluminum target

Modulus of Elasticity, E (N/mm^2)	65762.0
Poison's Ratio, ν	0.3
Density, ρ (kg/m^3)	2700.0
Yield Stress, A (N/mm^2)	148.361
B (N/mm^2)	345.513
n	0.183
Reference Strain Rate, ε_0 (s^{-1})	1.0.0
C	0.001
m	0.859
T_{melt} (K)	893.0
T_0 (K)	293.0
Specific Heat, C_p (J/kg-K)	920.0
Inelastic heat fraction, α	0.9
D_1	0.071
D_2	1.248
D_3	–1.142
D_4	0.0097
D_5	0.0

to projectile impact. The ballistic limit, failure mode, global deformation and fracture behaviour of thin aluminum plates has been obtained by varying various geometric parameters of the target as well as the projectile and influence thereon the response of the target has been studied through experiments as well as numerical simulation.

4.1 Target Thickness

The thickness of target was varied as 0.5, 0.71, 1, 1.5, 2, 2.5 and 3 mm in order to study the influence on the ballistic resistance. Each target was hit by blunt ogive and hemispherical projectile nosed projectile of 19 mm diameter and 52.5 grams mass. The target specimen hit by the blunt projectiles failed through shear plugging and as such there was no influence of thickness on the failure mechanism, (Fig. 2(a)). Hemispherical projectile failed the target through petal formation and thinning. A single petal was formed in all the targets and failure mainly occurred through tensile stretching, Fig. 2(c). For ogival nosed projectile four equal size petals were formed in the plates of all thicknesses however, the bending of petals decreased with an increase in thickness; (Fig. 2(b)). It was also observed that for 0.5, 0.71, 1.0 and 1.5 mm thick plates the velocity drop was higher for blunt nosed projectile. On the other hand for 2, 2.5 and 3 mm thicknesses the velocity drop was higher for ogive nosed projectile. However, the ballistic limit velocities of both of these projectiles were found close to each other for a given thickness. Hemispherical nosed projectile on the other hand, was found to be the least effective penetrator, (Table 2).

4.2 Projectile Shape

The effect of projectile shape has been investigated by varying the caliber radius head (CRH) of the projectile from 0 to 2.5. The caliber radius head defined as the ratio of the nose radius to diameter of projectile was varied as 0, 0.5,1, 1.58, 2, and 2.5 keeping diameter of the projectile constant, 19 mm. The shape of the projectile thus varied as blunt, hemispherical and ogival as shown in Fig. 3.

The caliber radius head was found to have significant effect on the failure mode of 1 mm thick

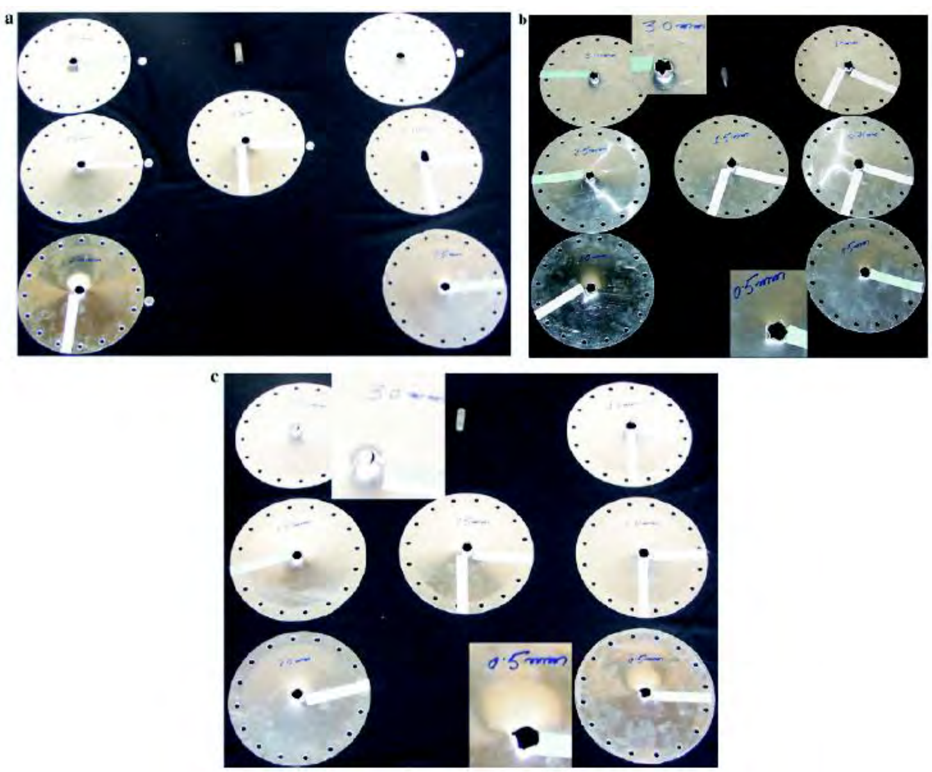

Fig. 2: Deformed plate specimens of various thicknesses impacted by (a) blunt nosed projectiles; (b) ogive nosed projectiles; (c) hemispherical nosed projectiles [4]

Table 2: Observed and predicted ballistic limits for different target thickness subjected to different projectile

Target thickness (mm)	Ballistic limit (m/s)					
	Ogive projectile		Blunt projectile		Hemispherical projectile	
	Observed	Predicted	Observed	Predicted	Observed	Predicted
0.5	37.21	44.03	41.75	45.57	45.44	46.81
0.71	41.33	47.75	47.12	47.87	51.75	53.01
1	48.29	54.69	67.64	70.34	67.29	69.75
1.5	58.59	60.74	67.77	68.82	72.52	73.67
2	75.42	79.45	74.82	77.28	88.87	91.03
2.5	88.05	92.07	80.84	83.33	101.37	102.77
3	93.67	95.75	90.47	92.42	112.36	116.50

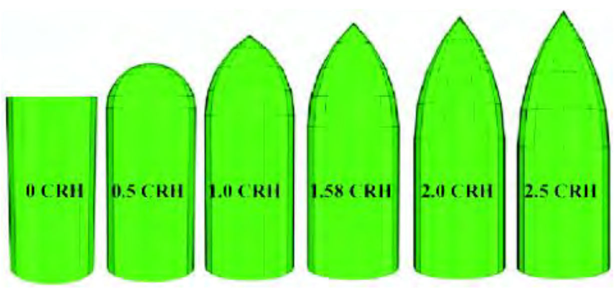

Fig. 3: Projectiles with different CRH [7]

aluminum target. Fig. 4 shows the failure modes of 1 mm thick 1100-H12 aluminum target impacted by the projectiles with varying caliber radius head. A significant effect of projectile nose shape has been found on the target failure mechanism. The first projectile with CRH 0 with blunt nose, failed the target by removing a circular plug equal to the diameter of projectile, Fig. 4(a). The ballistic limit of the target was found to be 75.0 m/s. The next projectile with CRH 0.5 with hemispherical nose, failed the target by significant thinning due to tensile stretching of contact material, Fig. 4(b). Formation of irregular petals was also observed in this case. The ballistic limit of the target was found to be 92.0 m/s. This is the highest ballistic limit among all the six projectiles shown in Fig. 5. It is revealed from here that the target has offered highest ballistic resistance against hemispherical nosed projectile. The projectiles with CRH 1.0, 1.58 and 2.0 failed the target through ductile hole enlargement and petal formation. Four petals were formed in the target impacted by each of these three projectiles, Fig. 4 (c)-(e). This is a typical failure mode of thin metallic plates impacted by pointed nose projectiles. The ballistic limit of the target for projectile with 1.0, 1.58 and 2.0 CRH was 57.28 m/s, 52.1 m/s and 55.5 m/s respectively. It is seen that the ballistic limit has not been influence by the nose radius of these projectiles. The last projectile with CRH 2.5 also failed the target through hole enlargement, however, petal formation did not occur in this case, Fig. 4 (f). The ballistic limit was found to be 54.0 m/s; almost

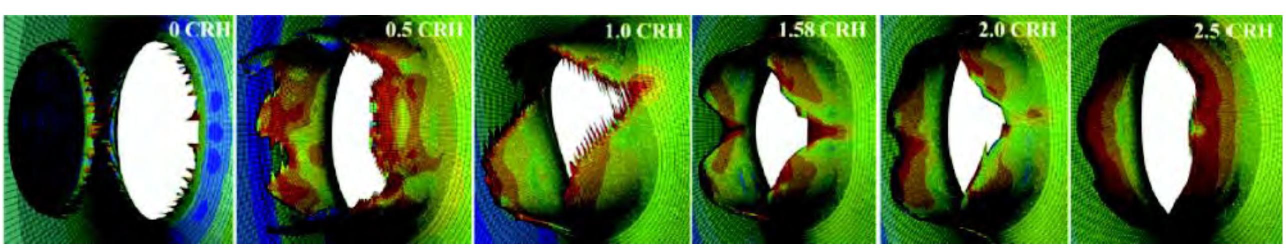

Fig. 4: Failure modes of target impacted by different nose shaped projectiles [7]

equivalent to that of the target impacted by 1.0, 1.5 and 2.0 CRH projectiles. It can be concluded here that ballistic resistance of target has not been influenced by the projectile nose radius if the nose shape of projectile is same (Fig. 5). However, when the nose shape is changed the ballistic limit has drastically affected.

The ballistic limit of 1 mm thick 1100-H12 aluminum target increased as the CRH increased from 0 to 0.5 and with further increase in CRH to 1.0, 1.5, 2.0 and 2.5 its values were found to drop quite significantly. The target offered highest ballistic limit against 0.5CRH (hemispherical) projectile followed by 0 CRH (blunt nosed) projectile while the ballistic limit of the target was found to be significantly lesser for 1.0, 1.58, 2.0 and 2.5 CRH (ogive nosed) projectiles.

4.3 Target Configuration

To study the effect of target configuration thin-layered plates arranged in various combinations such as three combinations of 1.5 mm equivalent thickness (3 x 0.5 mm, 2 x 0.71 mm and a monolithic plate of 1.5 mm thickness), four combinations of 2 mm equivalent thickness (4 x 0.5 mm, 3 x 0.71 mm, 2 x 1 mm and a monolithic plate of 2 mm thickness), three combinations of 2.5 mm equivalent thickness (5 x 0.5 mm, 4 x 0.71 mm and monolithic plate of 2.5 mm thickness) and three combinations of 3 mm equivalent thickness (3 x 1 mm, 2 x 1.5 mm thickness and monolithic plate of 3 mm thickness) were normally impacted by flat, ogive and hemispherical nosed projectiles. Fig. 6 shows the deformed specimens of 0.5 mm thick double and triple layered plate. Fig. 7 shows a typical comparison of observed and predicted energy absorption capacity of the target plates of total equivalent thickness 1.5, 2, 2.5 and 3 mm impacted by blunt, ogive and hemispherical nosed projectiles in different configurations.

For 2 mm equivalent thickness impacted by blunt and hemispherical nosed projectile [Figs. 7(a) and 7(c)] and 1.5 mm equivalent target thickness impacted by blunt nosed projectile [Fig. 7(d)] layered plate was found more efficient compared to monolithic plate. In the case of 1.5 mm equivalent target thickness impacted by ogive nosed projectile [Fig. 7 (e)] an opposite trend was observed which showed that three layered plate of 0.5 mm thickness absorbed highest kinetic energy followed by monolithic plate of 1.5 mm thickness and two layered plate of 0.71 mm thickness respectively. Bending and membrane stretching prominently governs the failure mechanism in this contrary case. Even though, the shear failure of the target plate was only observed in the case of blunt nosed projectile impact. Ogive and hemispherical

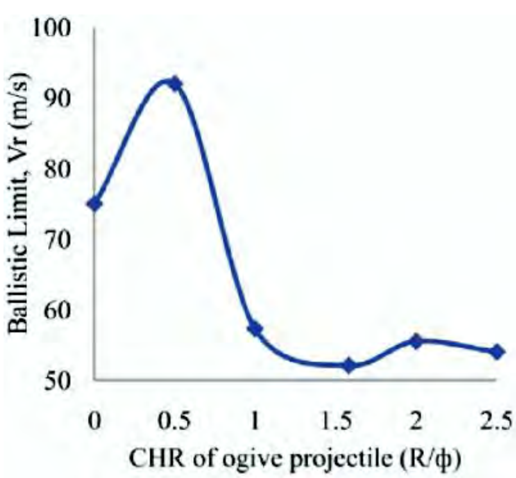

Fig. 5: Comparison of ballistic limit of ogive nosed projectile with different caliber radius head (CRH) [7]

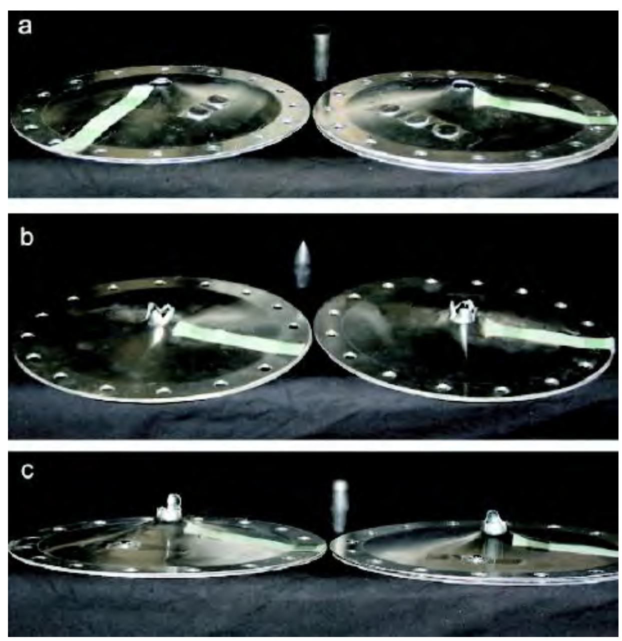

Fig. 6: Deformed specimens of layered target plates impacted by (a) blunt (b) ogive (c) hemispherical nosed projectiles [5]

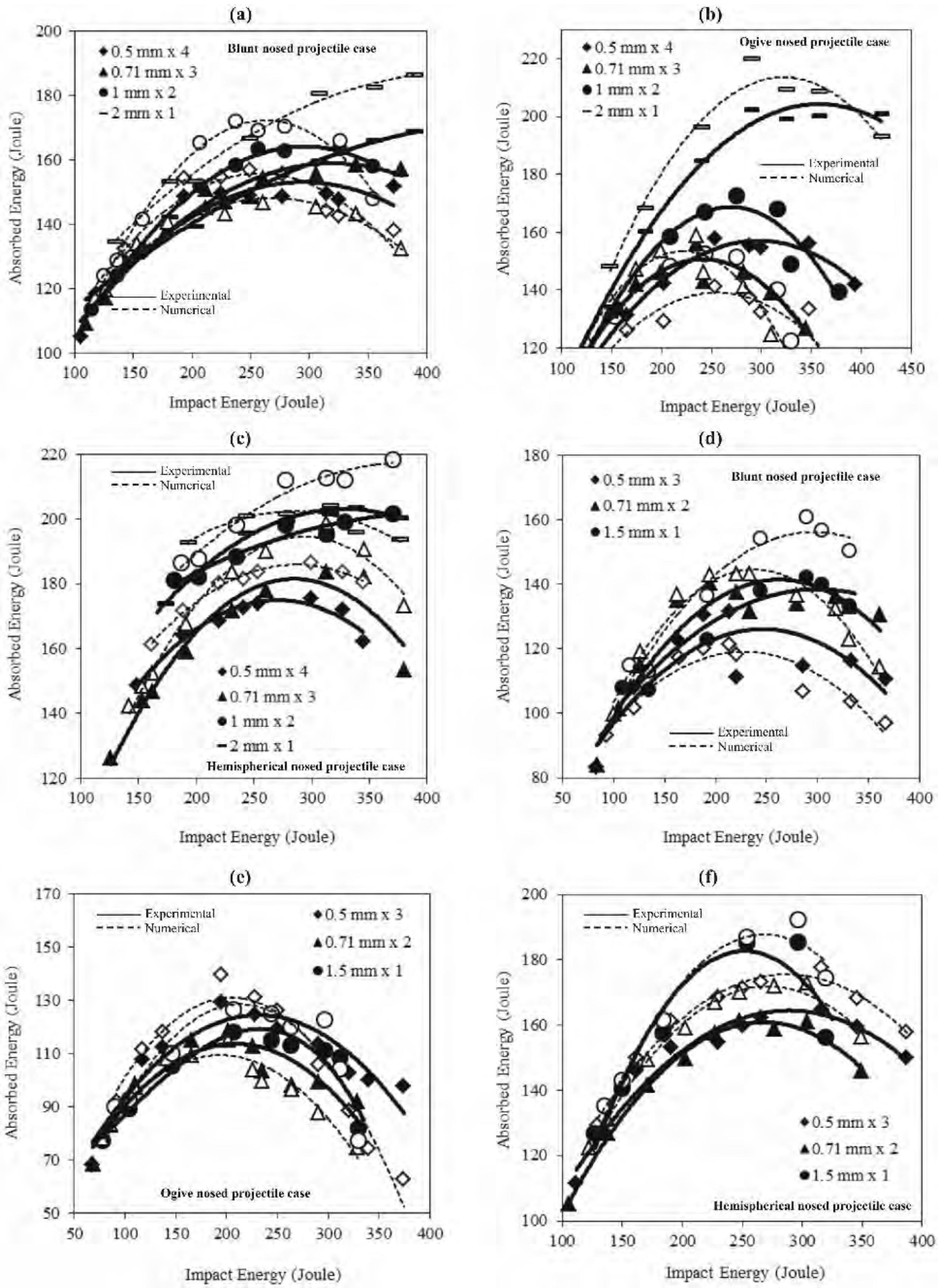

Fig. 7: Variation of observed and predicted energy absorption capacity of the target plates for varying configuration (... *Contd*)

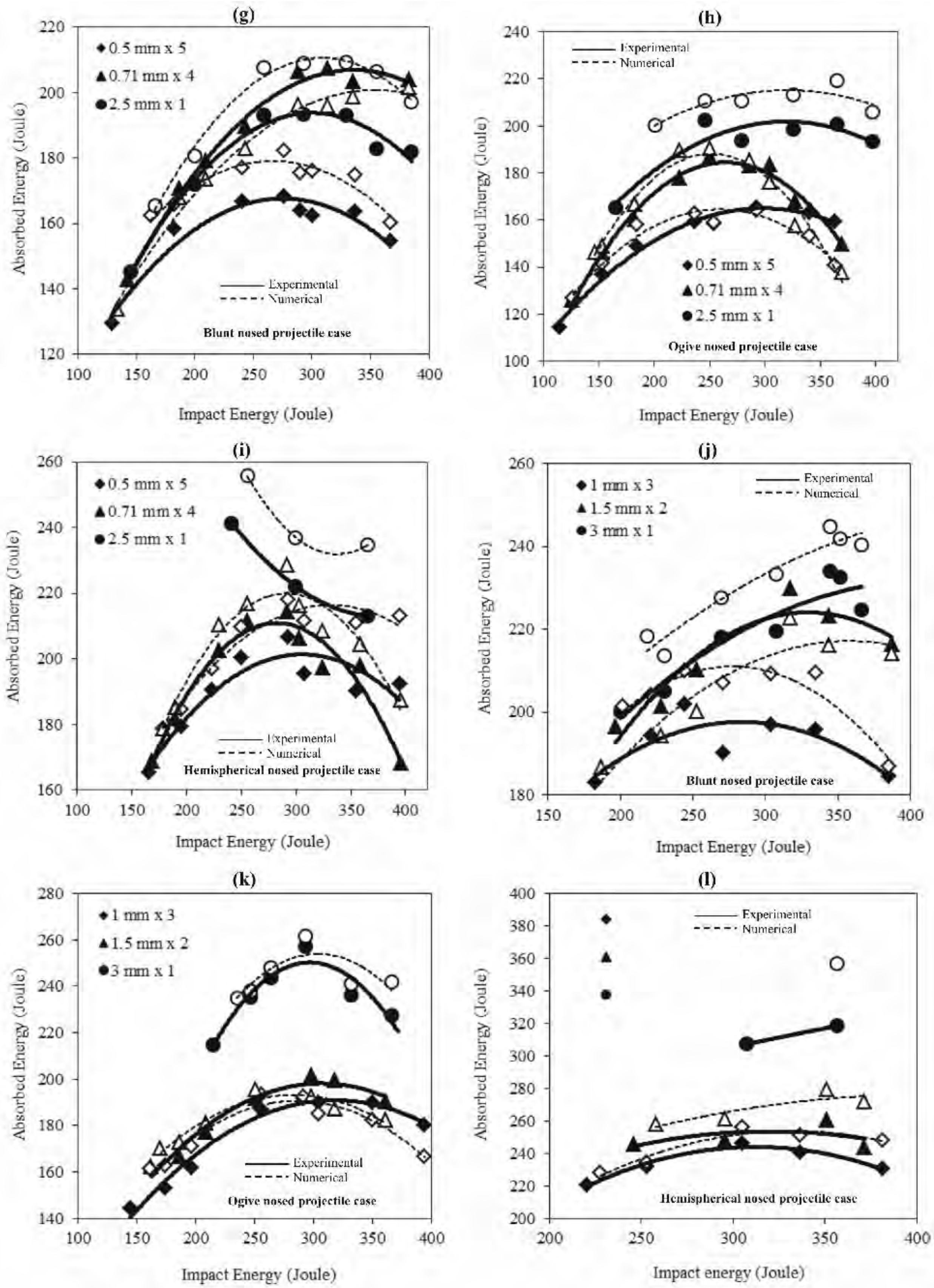

Fig. 7: Variation of observed and predicted energy absorption capacity of the target plates for varying configuration

nosed projectiles failed both single as well as layered target plates through bending and membrane stretching. Figs. 7(g)-(i) compare the energy absorption capacity of five layered plate of 0.5 mm thickness, four layered plate of 0.71 mm thickness and single plate of 2.5 mm thickness impacted by blunt, ogive and hemispherical nosed projectiles.

For blunt nosed projectile impact four layered plate of 0.71 mm thickness, which actually gives 2.84 mm total thickness, offered highest perforation resistance. On the other hand, for ogive and hemispherical nosed projectile impact single plate of 2.5 mm thickness offered highest resistance. This particular case clearly revealed that the there is considerable decrease in the resistance of the layered plate as compared to that of the monolithic plate.

It is also observed from Fig. 7(i) that the energy absorbed by the monolithic plate of 2.5 mm thickness impacted by hemispherical nosed projectile decreases continuously with an increase in impact energy. In all the other cases however, the absorbed energy initially increased up to a certain level and later it decreased with increasing impact energy. In the case of monolithic plate of 3 mm thickness impacted by hemispherical nosed projectile [Fig. 7(l)] perforation was observed at 356.57 Joule impact energy (116.55 m/s velocity) below which the projectile failed to perforate the target plate.

The influence of target configuration was further investigated for layered in contact and spaced targets of 1 mm equivalent thickness impacted by ogival as well as blunt nosed projectile. The spacing between the layers was varied as 2, 5, 10, 20 and 30 mm. The highest ballistic limit was observed for monolithic target followed by layered in-contact and spaced targets respectively. The variation of spacing between the layers did not cause significant influence on the ballistic limit. For ogive nosed projectile the ballistic limit of monolithic targetwas found to be 17.7% and 25.8% higher than the double layered in contact and 2 mm spaced target respectively, Fig. 8(a). The variation of spacing had insignificant effect on the ballistic limit. For blunt nosed projectile, the ballistic limit of monolithic target was found to be 2.7% and 8% higher than double layered in-contact and 2 mm spaced target respectively. The ballistic limit of layered in-contact target was found to be 5.2% higher than the 2 mm spaced target while, the ballistic limit of 2 mm spaced target was found to be 1%, 1.2%, 6.6% and 6.6% higher than 5 mm, 10 mm, 20 mm and 30 mm spaced target [Fig. 8(b)].

4.4 Angle of Incidence

To study the influence of angle of incidence on ballistic resistance the ogive nosed projectile was hit on monolithic as well as double layered plates of equivalent thickness 1 mm. The monolithic plate was impacted at 0°, 15°, 30°, 45° and 60° obliquity or until ricochet of the projectile occurred. Further, the double layered target of 0.5 mm thickness was impacted by ogive nosed projectile at 0°, 15° and 30° obliquity [6, 8]. It was observed that at normal impact the projectile follows the central axis whereas at oblique impact it has been found to deviate from the central axis; initially away and then towards the plate normal. The deviation of the projectile increased with an increase in angle of incidence and decrease in impact velocity. Fig. 9 shows the failed specimens of 1mm thick aluminum target impacted at varying angle of incidence.

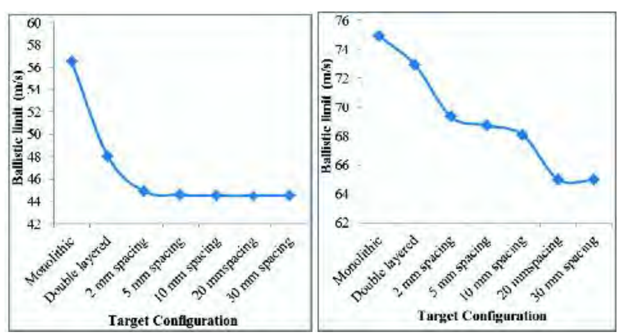

Fig. 8: Variation of ballistic limit with target configuration of 1 mm equivalent thickness (a) for ogive nosed projectile; (b) for blunt nosed projectile [9]

Fig. 9: Deformed specimens of 1 mm thick 1100-H12 aluminum target impacted at different obliquity [6]

At low obliquity, the resistance of the targets was found to be almost equivalent to that corresponding to the normal impact. As the angle of incidence increased, the target resistance was also found to increase and hence the ballistic limit. For oblique impact also the monolithic target witnessed higher ballistic resistance than that of the double layered in-contact targets of equivalent thickness. However, failure in both cases occurred through ductile hole enlargement and petal formation (Fig. 10). Four equal petals were formed at normal impact. The size of upper two petals decreased and that of the lower two petals increased with increase in obliquity. At 45° obliquity, the two smaller petals vanished while the two larger petals combined together and emerged in the form of an elliptical bulge (Fig. 10).

The ballistic limit of monolithic target was found to increase by 5.7%, 12.4% and 25.3% at 15°, 30° and 45° obliquity respectively as compared to that of the normal impact (Fig. 11). At 60° obliquity the ogive nosed projectile ricocheted at all the velocities employed. For double layered (2 x 0.5 mm) 1100-H12 aluminum target the ballistic limit was found to increase with an increase by 4.8% at 15° and 11.4% at 30° obliquity in comparison to that of the normal impact.

When the angle of incidence is very high, the projectile strikes the target and rebounds back with or without penetrating the target. This phenomenon is known as ricochet and the minimum angle at which it occurs is called critical angle of ricochet. Fig. 12 shows the ricochet phenomenon of ogival projectile impacted on 1 mm thick aluminum target at 73.3 m/s velocity and 49° angle of incidence. It has been observed that the critical angle of ricochet varies with the projectile impact velocity, nose shape and the target thickness. The variation in critical angle of ricochet of the ogive nosed projectile with impact velocity is shown in Table 3. The critical angle of ricochet was found to vary by 18° by varying the impact velocity by 60.2 m/s.

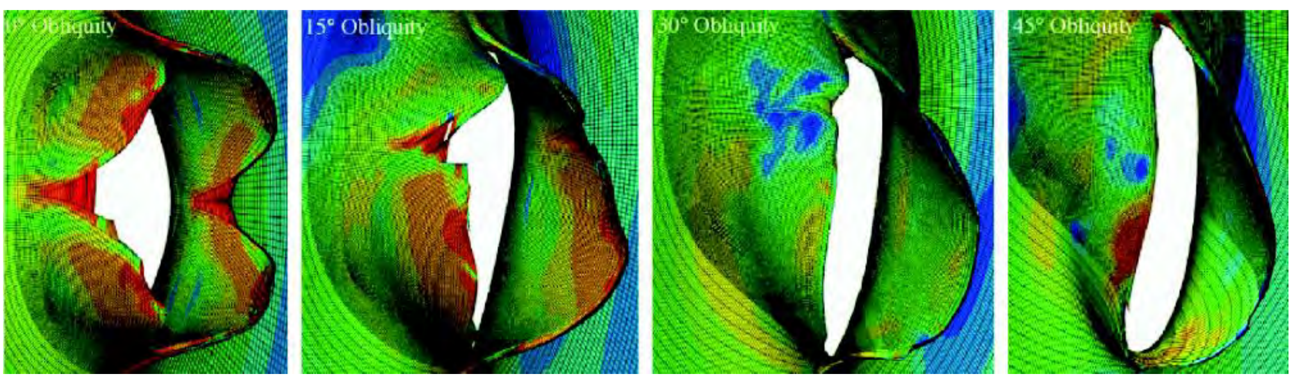

Fig. 10: Failure modes of 1 mm thick 1100-H12 aluminum target plates at different obliquity [8]

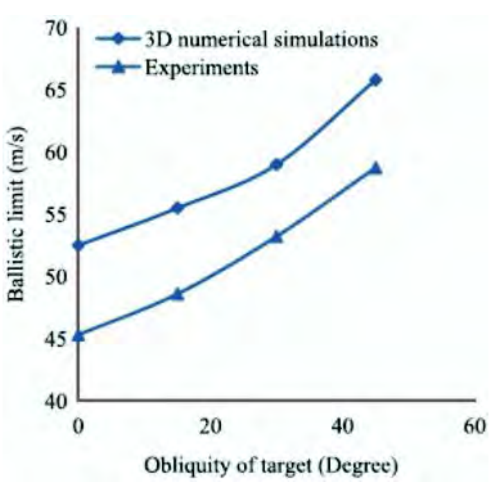

Fig. 11: Variation of ballistic limit with the angle of obliquity [8]

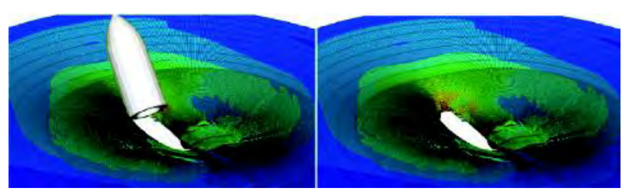

Fig. 12: Typical deformation pattern of ductile targets during projectile ricochet [8]

Table 3: Variation of critical angle of ricochet of ogive nosed projectile with impact velocity

Ogive nosed projectile impacted on 1 mm thick 1100-H12 aluminum target	
Impact velocity Vi (m/s)	Angle of Ricochet
112.72	60
97.23	56
82.97	52
73.3	49
65.8	47
57.28	44
52.5	42

5. Conclusion

An attempt has been made to bring together information about various aspects of the phenomena of impact response of single and layered thin plates. The observations regarding influence of target thickness, projectile shape, target configuration and angle of incidence on ballistic resistance are reviewed. Major findings are as follows:

The target thickness highly affects the ballistic resistance. The ballistic limit for 3 mm thick target was found to be 60.2%, 55.8%, 48.4%, 37.4%, 19.4% and 5.9% higher compared to 0.5, 0.71, 1, 1.5, 2 and 2.5 mm thick target respectively for ogival projectile impact. The same was found to be 53.8%, 47.9%, 25.2%, 25%, 17.2% and 10.6% for blunt projectile and 59.5%, 53.9%, 40.1%, 35.4%, 20.9% and 9.7% higher for hemispherical nosed projectile impact.

It was found that the ballistic resistance of target has not been influenced by the projectile nose radius if the nose shape of projectile is same. However, when the nose shape is changed from blunt to hemispherical and ogival, the ballistic limit has been found to be drastically affected.

In general monolithic targets are found to offer more resistance compared to layered and spaced target. The ballistic limit of monolithic target was found to be 17.7% and 25.8% higher than the double layered in contact and 2 mm spaced target hit by ogive nosed projectile. For blunt projectile the same was found to be 2.7% and 8% higher than double layered in-contact and 2 mm spaced target. The variation of spacing had insignificant effect on the ballistic limit for both ogive and the blunt nosed projectiles.

The ballistic resistance of a given target has been found to increase with an increase in angle of incidence. The ballistic limit of monolithic target was found to increase by 5.7%, 12.4% and 25.3% at 15°, 30° and 45° obliquity respectively as compared to that of the normal impact. For double layered (2×0.5 mm) target the ballistic limit increased by 4.8% at 15° and 11.4% at 30° obliquity compared to normal impact. The critical angle of ricochet was found to be a function of impact velocity, projectile shape and target thickness.

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