Impact Response of Single and Layered Thin Plates-Review

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Abstract

This paper reviews recent research into the penetration and perforation of single and layered thin plates. It is shown that over the last few years there has been a significant amount of experimental as well as numerical research into a wide range of projectile-target configurations. Although most of this research has been concerned with the normal impact of monolithic metallic plates by non-deformable projectiles, valuable work has also been carried out on non-normal impact as well as layered thin targets. Recent numerical investigations that enable the important characteristics of the penetration and perforation process to be modelled are reviewed. These include models that predict local deformations and failure, global deformations or both. The development of numerical codes that predict target response to projectile impact is briefly reviewed and the capabilities and limitations of current codes are discussed.

Introduction

The field of Impact Dynamics covers an extremely wide range of situations and is of interest to engineers from a number of different disciplines. For example, production engineers are interested in the subject in respect of its application to high speed blanking and hole-flanging processes; military scientists need to understand the subject in order to design structures that are more efficient at withstanding projectile impact or in order to design improved ballistic missiles;

geologists use improved understanding of earth penetration processes to carry out remote seismic monitoring and surveying; and vehicle manufacturers use their understanding of the response of structures to impact loading to improve the performance and safety of their products. The general nature of the subject means that it incorporates a wide range of spatial, temporal and thermal scales, and also a wide range of materials. It also covers a large variety of loading situations such as hypervelocity impact, blast loading, jet impact, projectile penetration, dropped-object loading, structural crushing etc.

Design of metal shields for protection against projectiles impact has long been of interest in military and civilian applications. Penetration and perforation related problems have been studied for a long time, and substantial efforts have been made by experimental, numerical and theoretical investigations in order to understand the phenomena occurring in the target impacted by projectile. When a single plate is replaced by several layered thin plates, the order, thickness, number of layers and the air gap between layers affect the failure models, which lead to the difference of the ballistic resistance between various configuration targets. Although there were a number of studies dealing with the ballistic behavior of multi-layered plates, but their scope was limited when compared to studies of monolithic plates.

Experimental Investigations

Experimental investigations of ballistic resistance of layered thin aluminum target were carried out by Radin and Goldsmith [2]. The hard-steel blunt and conically-nosed projectiles were hit on multi-layered plates of soft aluminum; both adjacent and spaced with the help of a pneumatic propulsion device using compressed nitrogen. The ballistic resistance of the metallic monolithic target was found to be greater than that of several adjoining plates of the same thickness; this was considered to be due to the greater bending resistance of the former.

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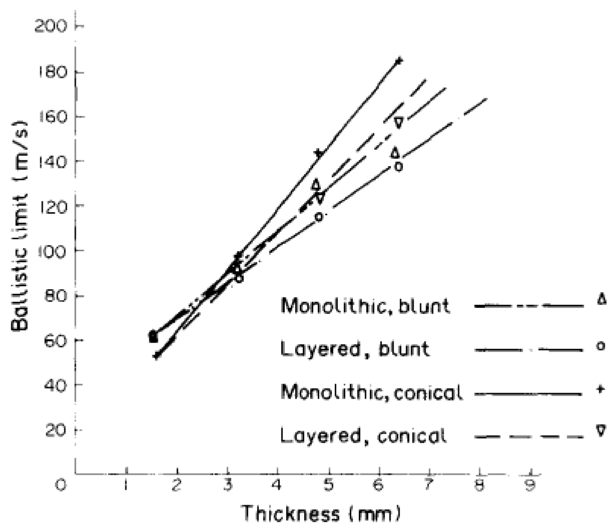

Fig. 1:- Ballistic limits of monolithic and layered aluminum plates as a function of target thickness for blunt and conical-nosed strikers[2]

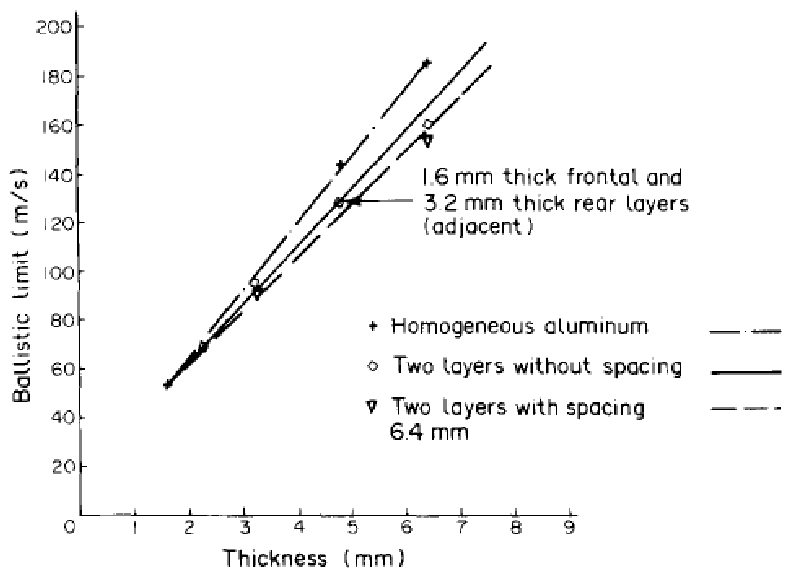

Fig. 2:- Ballistic limit of two layers of 2024-0 aluminum targets, adjacent or spaced, 6.4 mm apart, struck by conically-tipped projectiles [2]

The experimental ballistic limits for monolithic targets of the two materials were compared to predictions of other investigators for both the blunt and conically-tipped strikers, derived from simple models of the process.

In continuation to ballistic research work, Gupta et al. [7] studied the perforation study of single plates of aluminum of various thicknesses subjected to normal impact by ogive nosed projectiles. Based on the mechanism of deformation observed and the data of residual and incident velocities, analytical and empirical relations have respectively been developed for the determination of both residual velocity and ballistic limit.

Analytical relation for residual velocity was as follows:-

$$v_r = \sqrt{v_i^2 - \frac{2W}{m}}.$$

Where m = mass of projectile, W = total work done in deformation of plate, v_i= impact velocity, v_r= residual velocity

The empirical relation for residual velocity was as follows:-

$$v_r = \sqrt{v_i^2 - \frac{kdY}{m} h_0^{2n}}.$$

Where k, n=constant, h_0= original thickness, Y= yield strength

These relations are seen to match the experiments well. The plates employed were cut out of commercial purity aluminium (&99%) sheets of thicknesses 0.5, 0.74, 1.0, 1.5 and 2.0 mm. Circular targets of 255mm total diameter with 205mm diameter free span were made from these plates and used in as received condition.

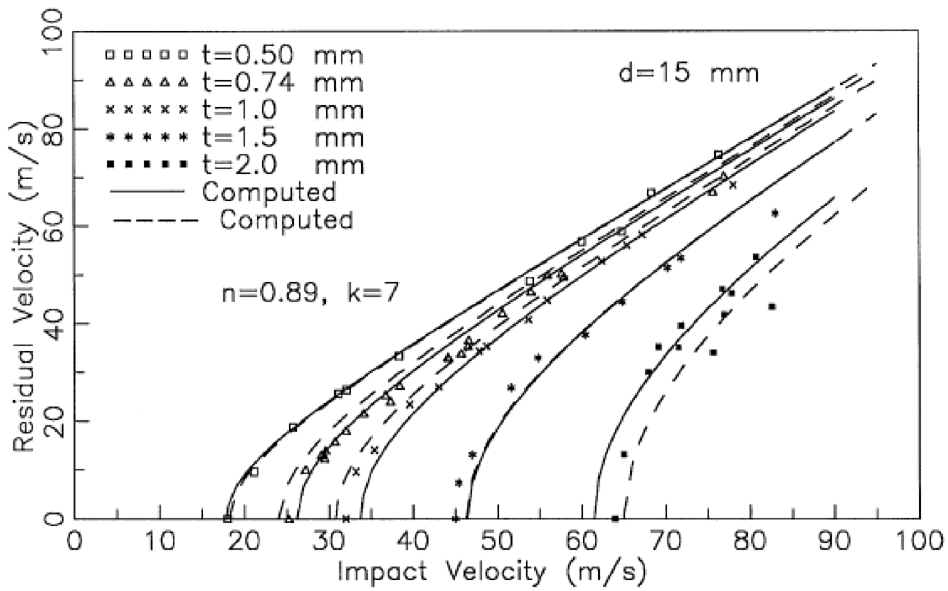

Fig. 3 :- Experimental results of residual velocities versus impact velocities for aluminium plates of different thicknesses along with curves obtained from analytical and empirical relation.

Similarly single and three layered structure was studied by Nia and Hoseini [16]. Experimental study was performed by hitting a hemispherical nosed projectile on monolithic and layered target of Al 1100. The single layer target wass 3 mm thick and the thicknesses of layers of the three layered targets were 0.5, 1 and 1.5 mm. The multi-layered targets were tested both when the layers were in-contact and spaced (with air gaps). The results showed that the single layer targets have greater ballistic limit velocities than multi-layered targets. Furthermore, the ballistic limit velocity of in-contact layered targets was greater than that of spaced layered targets.

Similar type of study was done by Wei et al[18] to perform some impact tests on monolithic and multi-layered metal plates subjected to impact by blunt rigid projectiles. The results showed that the monolithic targets were more effective than layered targets when the dominant response of monolithic targets was dishing which involved membrane stretching, and the ballistic limit velocities of layered plates decreased with the increase of the number of layers.

Moreover, the air gap significantly affected the ballistic resistance of spaced layered plates. Layered targets with larger air gap were stronger than those with small air gap, and also there were two ballistic limit velocities in the former configuration. On the other hand, as the order of layers affected the ballistic resistance of double-layered targets, the ballistic resistance was better when the first layer was thicker than the second layer.

In continuation to this research work Deng etal.[19] performed some experiments by hitting hemispherical nosed projectile on single, double-, three-, four- and six-layered plates. Similar type of conclusion was found that the monolithic thin targets presented more effective ballistic resistance than multi-layered targets. However, the monolithic targets had lower ballistic resistance than multi-layered targets if the total thickness above a specific value. The target response changed from shearing to bulging and dishing when using multi-layered targets instead of monolithic targets. Moreover, the air gap decreased the ballistic resistance of multi-layered targets, but the air gap size had slight influence on the ballistic resistance. The order of layers affected the ballistic resistance of multi-layered targets; the multi-layered targets of two equal thick plates had the highest ballistic resistance followed by multi-layered targets of a thicker front plate and a thinner back plate, multi-layered targets of a thinner front plate and a thicker back plate.

In series of experimental investigation Deng et al.[20] conducted some impact test on thin multi-layered plates arranged in various combinations of the same total thicknesses. The results show that the thin monolithic targets have greater ballistic limit velocities than multi-layered targets if the total thickness less than a special value, and also the ballistic limit velocities of multi-layered targets decrease with the increase of the number of layers. Otherwise, the moderate thickness monolithic targets give lower ballistic limit velocities than multi-layered targets. The contradictory conclusion was found that the ballistic resistance of the multi-layered targets was better when the first layer is thinner than the second layer. Furthermore, the ballistic limit velocities of in-contact multi-layered targets were greater than those of spaced multi-layered targets.

Numerical investigations

In 2004 Dey et al. [9] studied the effect of target strength on the perforation of 12 mm-thick steel plates of Weldox 460 E, Weldox 700 E and Weldox 900 E impacted by blunt, conical and ogival nosed projectiles. The mechanical tests were performed to determine the parameter of Johnson–Cook constitutive equation and fracture criterion which include the effects of strain hardening, strain rate hardening, temperature softening and stress triaxiality on material strength and ductility.

Table:-1 Model constants for the three materials [9]

Material		Weldox 460 E	Weldox 700 E	Weldox 900 E
Yield stress	A (MPa)	499	859	992
Strain hardening	B (MPa)	382	329	364
	n	0.458	0.579	0.568
Strain rate hardening	C	0.0079	0.0115	0.0087
Temperature softening	m	0.893	1.071	1.131
Fracture strain	D_1	0.636	0.361	0.294
	D_2	1.936	4.768	5.149
	D_3	−2.969	−5.107	−5.583
	D_4	−0.014	−0.0013	0.0023
	D_5	1.014	1.333	0.951

Numerical simulations were carried out using the non-linear finite element code LS-DYNA. The results were validated from experimental results. A compressed gas gun was used to launch projectiles within the velocity range from 150 to 350 m/s. The initial and residual velocities of the projectile were measured with the help of a digital high-speed camera system. The experimental results indicate that for perforation with blunt projectiles the ballistic limit velocity decreases for increasing strength, while the opposite trend is found in tests with conical and ogival projectiles.

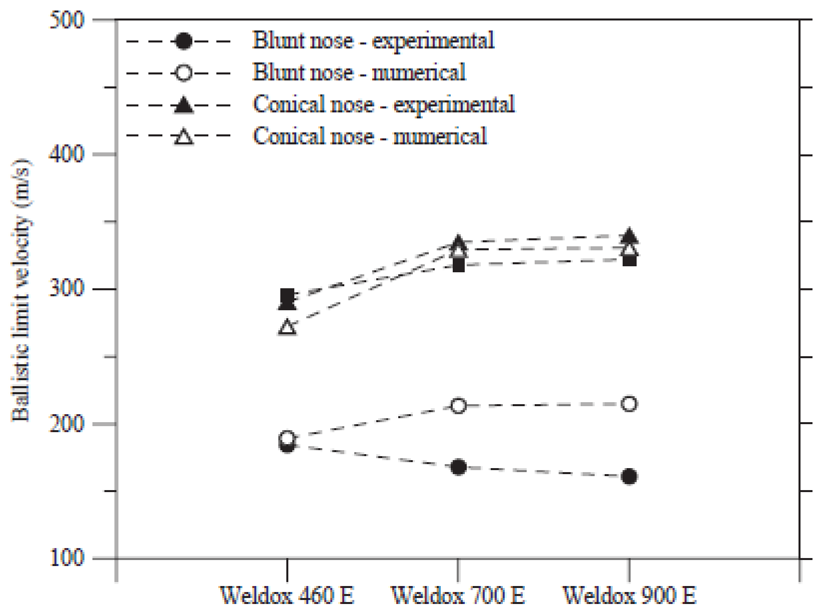

Fig. 4 :-Ballistic limit velocity for the three materials for blunt- and conical-nosed projectile: comparison between experimental and numerical results [9]

In continuation to material characterization Borvik et al. [6] formulated constitutive model of viscoplasticity and ductile damage of the behavior of Weldox 460 E steel as shown in following table.

Preliminary model constants for Weldox 460 E steel

Elastic constants and density			Yield stress and strain hardening			Strain rate hardening		Damage evolution	
E (GPa)	ν	ρ (kg/m^3)	A (MPa)	B (MPa)	n	$\dot{p}_0, \dot{r}_0$ (s^{-1})	C	D_c	p_d
200	0.33	7850	490	807	0.73	$5 \cdot 10^{-4}$	0.012	0.30	0

Adiabatic heating and temperature softening					Fracture strain constants				
C_p (J/kgK)	α	T_m (K)	T_0 (K)	m	D_1	D_2	D_3	D_4	D_5
452	0.9	1800	293	0.94	0.0705	1.732	-0.54	-0.0123	0

12mm thick Weldox 460E steel plates were impacted by blunt-nosed cylindrical projectiles in the lower ordnance velocity regime. The non-linear finite element code LS-DYNA, were used to simulate the phenomena. All targets failed by shear plugging. A metallurgical examination of the penetrated target plates is also presented. This has revealed void growth in the localised shear zone, indicating a ductile fracture.

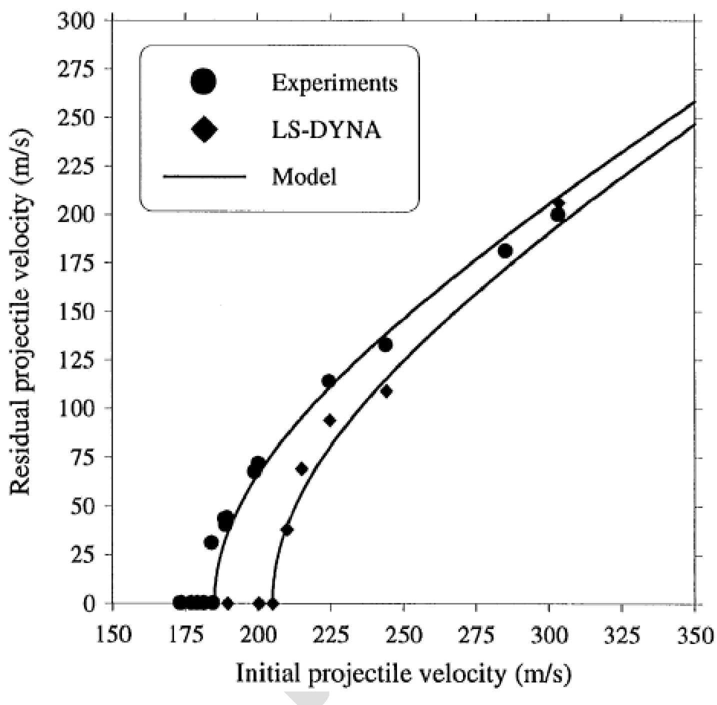

Fig. 5 :- Predicted and observed residual velocities

In addition to steel, ballistic investigations was performed on thin aluminum plate [11,12,16-17]. Different aluminum alloys were characterized by different mechanical tests. Ballistic resistance of thin plates was investigated by hitting by different nosed projectile. In 2008, Gupta et al.[11] carried out experimental and numerical investigations of deformation behavior of layered aluminum plates of different thicknesses under the impact of flat, hemispherical and ogive nosed Thin-layered plates arranged in various combinations were normally impacted at different velocities with the help of a pneumatic gun steel projectiles.

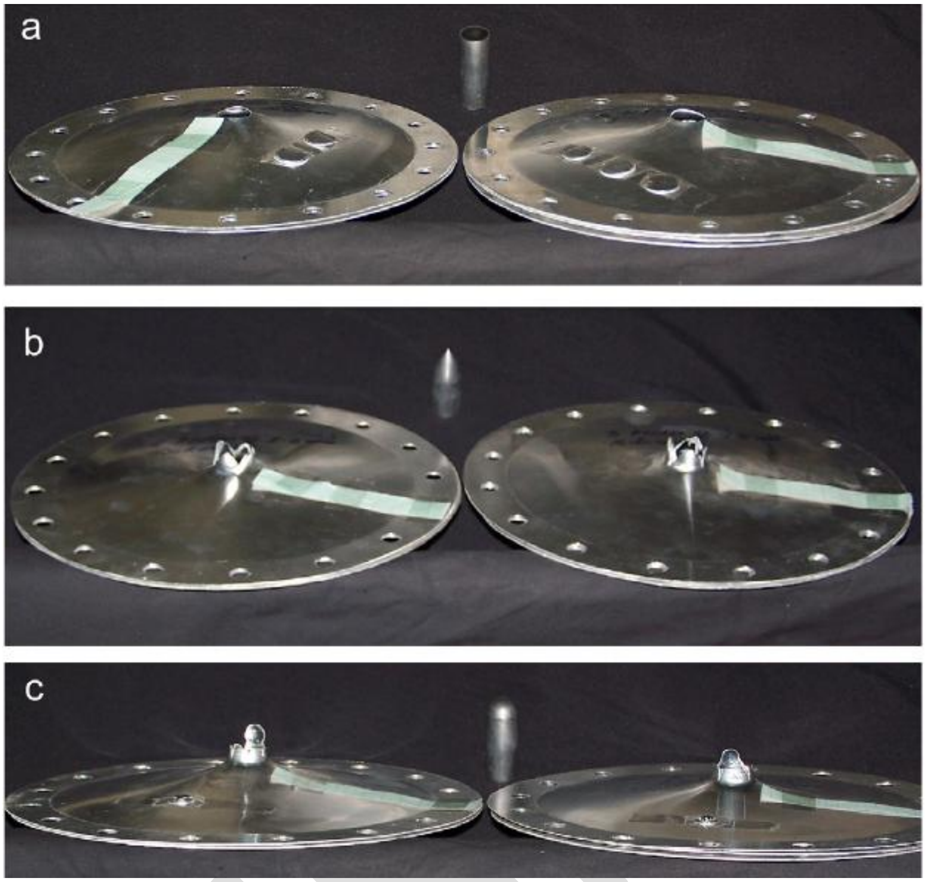

Figure 6: Deformed shape of the target subjected to different nose shape projectile

Ogive nosed projectile was found to be the most efficient penetrator of the layered target. Hemispherical nosed projectile required maximum energy for perforation. Numerical simulation of the problem was carried out using finite element code ABAQUS.

Besides nose shape effect, the influence of obliquity with configuration on ballistic resistance was also studied [12]. Numerical simulations were carried out to study the behavior of Weldox 460 E steel and 1100-H12 aluminum targets impacted by conical and ogive nosed steel projectiles respectively [12]. Weldox 460 E steel targets of 12 mm thickness in single and double layered combination (2×6 mm) and 1100-H12 aluminum targets of 1 mm thickness in single and double layered combination (2×0.5 mm) impacted at 0°,15° and 30° obliquity were considered for simulations. Monolithic targets were found to have higher ballistic resistance than that of the layered in-contact targets of equivalent thickness. Failure of both the targets occurred through ductile hole enlargement. However, ogive nosed projectile failed 1 mm thick aluminum target through petal formation and conical nosed projectile failed 12 mm thick steel target through a circular or elliptical hole enclosed by a bulge at rear surface.

The only study which shows the effect of span of monolithic plate as well as configuration on ballistic resistance of aluminum plate was appeared to be undertaken by Iqbal et al. [17]. 1 mm thick 1100-H12 aluminum targets of varying span diameter and configuration were impacted by blunt and ogive nosed projectiles of 19 mm diameter and 52.5 g mass. The effect of target span was studied by varying the span diameter of 1 mm thick monolithic target as 50 mm, 100 mm, 204 mm, 255 mm and 500 mm. The ballistic limit was found to increase with increase in target span diameter for both the projectiles.

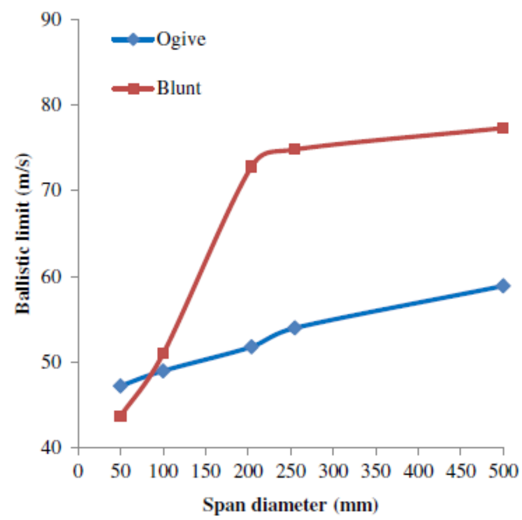

Figure 7:- Variation of ballistic limit with the target span diameter

The effect of configuration was studied by taking the monolithic, double layered in-contact and double layered spaced targets of 1 mm equivalent thickness and 255 mm span diameter. The spacing between the layers was varied as 2 mm, 5 mm, 10 mm, 20 mm 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 have significant influence on the ballistic limit in the case of ogive projectile but some effect was seen in the case of blunt projectile.

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