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Effect of In-Plane Biaxial Compression Force on Penetration Resistance for Steel Plate

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1. ABSTRACT

The importance of penetration and perforation in to targets in both military and civilian applications has made it the subject of many investigations. But the bulk of these investigations was experimental rather than analytical or numerical because of complexity of the governing equations. Hence most of the existing models are either mathematically rigorous or so simplified that they neglect many important parameters. Moreover, weight and cost are among the most important consideration in the design of perforation resistant systems (containment shields). Therefore, the present investigation has focused on the perforation and penetration of relatively thick metallic targets by rigid cylindro-ogival projectiles. To achieve the experimental part of this work a locally manufactured compression device was built for this purpose where the target plate was subjected to biaxial compression load of about 0.6 of its buckling load. A life 7.62 mm ammunition with steal projectiles have been used to impact the targets at 400 and 600 m/s thus the exit velocity in terms of the impact velocity and the total work done at the target was derived for the case of biaxial compression. Comparison of the experimental and the analytical results showed a good agreement while targets in the state of compression showed about 80% improvement in penetration resistance.

Nomenclature

Symbol	Notation	Unit
c	Crack length	mm
D	Flexural stiffness of plate	N.m
E	Young's modulus	N/m^2
e	Base of natural logarithm	
h_o	Target thickness	mm
m	Projectile mass	g
M_o	Fully plastic bending moment	N.m/l
M_r	Radial bending moment circumferential length	N.m/l
M_Θ	Hoop bending moment circumferential length	N.m/l
N_r	Membrane stretching force per unit circumferential length	N/m
N	The critical force Biaxial buckling	N/m
P	Central load	N
P_o	Plastic collapse load of the structure	N
P_c	Buckling load	N
R	Affected radius	mm
U	Plate elastic strain energy	J
V_i	Initial velocity	m/s
V_o	Finial velocity	m/s
ν	Passion's ratio	
W_B	Buckling work	J
W_D	Dishing work	J
W_e	Total elastic work	J
W_{EP}	Elastic work by penetration process	J
W_{EC}	Elastic work by Buckling	J
W_P	Petaling work	J
W_I	Indentation work	J
W_T	Total work	J
w_o	Maximum bulge height at plate center	mm
W_c	Central elastic deflection	mm
W_{Max}	Maximum central elastic deflection	mm
β	Projectile cone apex angle	degree
Δ K.E	Kinetic energy	J

2. Introduction

Situations involving impact are currently receiving widespread attention. At one time, impact problems were of primary concern to the military applications, now however, a sophisticated civilian technology is rapidly growing and sever demands are being made on the behavior of materials under very short duration of loading where safe and cost effective design demands a rigorous understanding of the behavior of impulsive loading for such diverse application as the protection of occupants or cargo during the crash of vehicles' body armor system for protection of police officers, executives, protection of spacecraft from meteoroid impact, explosive forming and welding of metals and many other application.

Calder and Goldsmith[1] in 1971 studied experimentally the dynamic response of thin plated subjected to the projectiles hit. **Awerebuch and Bonder [2]** in 1974 constructed a mathematical model to describe the mechanism of normal perforation process. **Wood word [٣]** in 1978 has shown that Taylors model for the penetration of thick metal target by conical projectiles is a good lower bound solution. **Nisim Levy and Werner Goldsmith [4]** in 1984 developed the constitutes of a very elementary analysis of the penetration and perforation processes involved in normal impact of thin plates by himspherically–tipped cylindrical hard steel projectiles. **Virostek, Dual and Goldsmith in 1987 [5]** conducted an experimental investigations of the force produce by the penetration and perforation of thin aluminum and steel plates by cylindro–conical and hemispherically-tipped projectiles. **Crouch, Baxter and Woodward in 1990 [6]** presented a series of mechanical and ballistic tests designed to test the material performance of a model for the perforation of thin metallic plates by blunt cylindrical missiles. Tensile, bending, and shear tests data show reasonable concurrence with the simplified forms assumed for the model. **Forrestal, Tzou and Longcope In 1995 [7]** developed penetration equations for rigid spherical-nose rods that penetrate ductile metal targets. **Borvik, Hopperstad, Berstad and Langseth in 2001 [8]** studied the penetration projectiles with three different nose shapes (blunt, hemispherical and conical). **Gupta in 2006 [9]** conducted experimentally on aluminum plates by using a gas gun and projectiles with blunt and hemispherical noses. **Hernandez, Murr and Anchondo in 2006 [10]** investigated the Stainless steel spherical projectiles which were impacted thick targets of nickel, copper, 304 stainless steel, and 70/30 brass at velocities ranging from 0.52-5.12 km/s.

3. The aim of the work

This work is concerned with the problem of penetration of actual ogival projectiles reasonably thick steel plate which is in the state of biaxial compression. The work comprises of theoretical solution supported by experimental process.

4. Theoretical Formulation

4.1 General Consideration

penetration and perforation of rigid ogival projectiles into single thick metallic targets which are under biaxial compression is considered. The idealization of the projectile behavior as a rigid body greatly simplifies the analysis of the process. From the definition of rigidity the only permissible effected element must undergo local displacements that accommodates its shape to that of the intruding projectile. These displacements result in forces on the projectile that, in turn, change its motion. An analytical model of penetration by a rigid projectile must delineate these kinematic changes and their influences. Analytical models of penetrations and perforations of single targets can be classified to fall in to the following groups in accordance with the principle that associates the kinematic changes in the target element material to the rigid projectile motion [11]:

1- Force time method (Newton's second law of motion).
2- The momentum method.
3- The energy method.

The energy method is of interest in this work, because it is the most successful so far among the other methods. In this method, the loss of kinetic energy of the projectile is equated to the work done in the deformation of the target, which implies that a failure criterion be assumed for both the localized influence of the projectile and the structural influence. The criterion for the localized influence is chosen according to the expected type of failure, (e.g. petaling, plugging …..etc.). While the criteria for structure influences depends on the idealization of target material behavior as one of the following [12]:

1- **Elastoplastic**: Where the effect of strain rate is neglected.
2- **Elasto-viscoplastic**: Where consideration of strain rate of the constitutive equation of material behavior is taken into account.
3- **Membrane model**: Where stress gradients across plate thickness and bending effects are neglected.

4.2 Monolithic target model in the state of no compression [11]

The analysis model of the penetration and perforation of an ogival rigid projectile against a reasonably thick metal target plate clamped with no compression at its outer periphery will be based on the energy approach where the loss in the kinetic energy of the projectile is equal to the required total work done in the deformation of the target W_T, thus:

$$\Delta K.E = \frac{1}{2} m(V_i^2 - V_o^2) = W_T \quad (1)$$

This total work is comprised of the following parts:

$$W_T = W_E + W_D + W_P + W_I \quad (2)$$

Where:

- **Elastic Work** W_E

$$W_E = \frac{P_o^2}{2K} = 0.00756\frac{\pi^2\sigma_y^2}{E}h_o a^4(1-v^2) \quad (3)$$

- **Plastic work done in dishing** W_D

$$W_D = \frac{\pi}{4}\sigma_y h_o w_o e^{-2\frac{\alpha c}{R}}\left[1+\frac{2\alpha c}{R}\right] + \frac{\pi}{2}\sigma_y h_o^2 w_o e^{-\frac{\alpha c}{R}}\left[2+\frac{\alpha c}{R}\right] \quad (4)$$

- **The Work Done in Indentation W_I**

$$W_I = \frac{2\pi\sigma_y h_0^3}{\sqrt{3}\tan\frac{\beta}{2}} \quad (5)$$

- **Plastic Work Done in Petalling W_P**

$$W_P = \frac{\pi}{2}\sigma_y c h_0^2(\theta_2-\theta_1) + \frac{\pi}{12}\rho c^2 h_0 \cos^2\theta_2 V_o^2 + \frac{1}{4}m\frac{k(3+2k)}{(1+k)^2} \quad (6)$$

Substituting and solving **Eqs 1** for $\mathbf{V_0}$ yields:

$$V_o = \left[\left(\frac{2+k}{2(1+k)^2}V_i\right) - \left(0.01512\frac{\pi^2\sigma_y^2}{mE}h_o a^4(1-v^2)\right) - \left(\frac{\pi}{2m}\sigma_y h_o w_o e^{-2\frac{\alpha c}{R}}\left[1+\frac{2\alpha c}{R}\right] + \frac{\pi}{m}\sigma_y h_o^2 w_o e^{-\frac{\alpha c}{R}}\left[2+\frac{\alpha c}{R}\right]\right) - \left(\frac{\pi}{m}\sigma_y c h_o^2(\theta_2-\theta_1) + \frac{4\pi\sigma_Y h_0^3}{m\sqrt{3}\tan\frac{\beta}{2}}\right)\right]^{\frac{1}{2}} \quad (7)$$

4.3 Monolithic target model in under biaxial compression

The analysis of model of the penetration and perforation of an ogival rigid projectile of a reasonably thick metal target plate clamped under biaxial compression will be also based on the energy approach where the loss of the kinetic energy of the projectile is equal to the required total work done in the deformation of the target W_T as given in **Eq. 1**

ΔK.E= $\frac{1}{2}m(V_i^2 - V_o^2) = W_T$, and

$$W_T = W_{EP} + W_D + W_P + W_I \quad (8)$$

where $W_{EP} = W_E + W_{EC}$

The components W_I and W_P will be the same as given earlier. However, the effect of biaxial compression will yield in appearing anew extra component in the elastic work which is: Elastic work W_{EC} due to compression [12]:

$$W_{EC} = 0.003655\frac{16P_o N a^4}{\pi^6 D} \quad (9)$$

Moreover, two new terms will appear in the expression for W_D which are a membrane stretching force per unit circumferential length N_r and a hoop stress per unit circumferential length N_c as shown in **Fig. 4-1** where

$N_r = \sigma_y h_o$ and $N_c = P h_0$ then:

$$W_D = \frac{\pi}{4}\sigma_y h_o w_o^2 e^{-2\frac{\alpha c}{R}}\left[1+\frac{2\alpha\alpha}{R}\right] + \frac{\pi}{2}\sigma_y h_o^2 w_o e^{-\frac{\alpha c}{R}}\left[2+\frac{\alpha c}{R}\right] - \frac{\pi}{4}P h_o w_o^2 e^{-2\frac{\alpha c}{R}}\left[1+\frac{2\alpha\alpha}{R}\right] - \pi P h_o^2 w_o e^{-\frac{\alpha c}{R}} \quad (10)$$

Substituting and solving Eqs 8 for V_0 yields

$$V_O = \left[\begin{array}{l} \left(\frac{2+k}{2(1+k)^2} Vi\right) - \left(0.01512 \ \frac{\pi^2 \sigma_y^2}{mE} h_o a^4 (1-v^2)\right) - \\ \left(2.806 \ \frac{\sigma_y N a^4}{Em \pi^5 h_o} (1-v^2)\right) - \\ \left(\frac{\pi}{2m} \sigma_y h_o w_o e^{-2\frac{\alpha c}{R}} \left[1+\frac{2\alpha c}{R}\right] + \frac{\pi}{m} \sigma_y h_o^2 w_o e^{-\frac{\alpha c}{R}} \left[2+\frac{\alpha c}{R}\right]\right) + \\ \left(\frac{\pi}{2m} P h_o w_o e^{-2\frac{\alpha c}{R}} \left[1+\frac{2\alpha c}{R}\right] + \frac{2\pi}{m} P h_o w_o e^{-\frac{\alpha c}{R}}\right) - \\ \left(\frac{\pi}{m} \sigma_y c h_o^2 (\theta_2 - \theta_1) + \frac{4\pi \sigma_y h_0^3}{m\sqrt{3} \tan \frac{\beta}{2}}\right) \end{array} \right]^{\frac{1}{2}} \qquad (11)$$

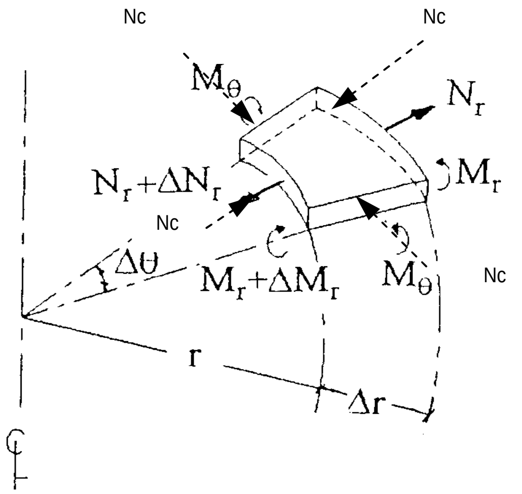

Figure 4-1 Bending and stretching affecting an element of the plate

5. Experimental Work

5.1 Impact velocity Testing setup

Fig (5-1) shows the block diagram of the universally used velocity measuring setup.[13]

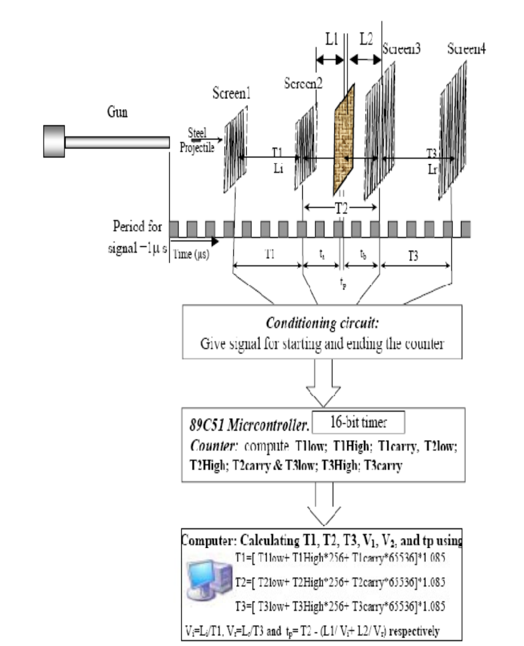

Figure 5-1 Block diagram of the velocity measurement device.

5.2. Biaxial compression device and its components

Fig (5-2) shows the locally made biaxial compression device.

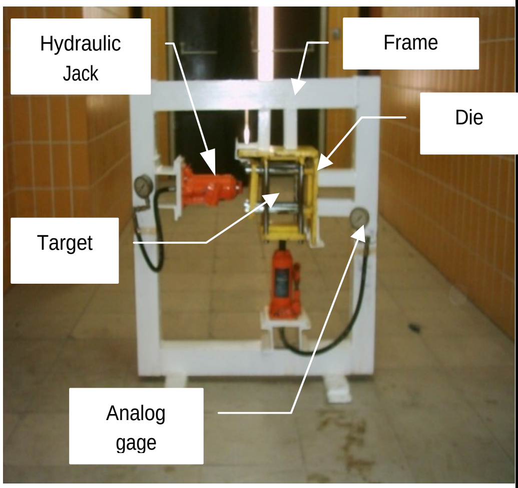

Figure 5-2 Biaxial compression device

A group of 3 shots were fired on each type of target and the average value was then taken in to consideration.

5.3 Materials

5.3.1 Projectiles:

Table 5
1 Chemical composition of the projectile material

C%	W%	Cr%	V%	Co%
0.8	18.5	4.5	1.25	5

Table 5
2 Mechanical properties of projectile

Material	Density kg/m^3	Modulus of Elasticity GPa	Ultimate strength in tension MPa	Yield strength in tension MPa
Medium Carbon steel	7850	400	850	450

5.3.2Targets:

Table 5
3 Mechanical properties of medium carbon steel

Material	Grade DIN	Density kg/m^3	Modulus of Elasticity GPa	Ultimate strength in tension MPa	Yield strength in tension MPa
Medium Carbon steel	45	7850	210	600	300

6. Results and Discussions

6.1 Experimental results

6.1.1 The target is at normal condition (no compression)

Table 6
1 The target is in the state of no compression

state of structure	Impact velocity m/s	Exit velocity m/s	% reduction in exit velocity
No compression	400	351	13.85
	600	560	6.66

6.1.2 Target is under equal biaxial state of compression ($F_X = F_y$)

Table 6-2 The target is in the state of equal biaxial compression

Loading F kN	Impact velocity m/s	Exit velocity m/s	% reduction in exit velocity
$F_x=F_y=0.2$ kN $0.2F_{buckling}=10.6$ kN	400	283	29.25
	600	500	16.6
$F_x=F_y=0.4F_b$ $0.4\ F_{buckling}=21.1$ kN	400	100	75
	600	250	58.3
$F_x=F_y=0.6F_b$ $0.6\ F_{buckling}=32.2$ kN	400	0	100
	600	110	81.6

6.1.3 Comparison of experimental results

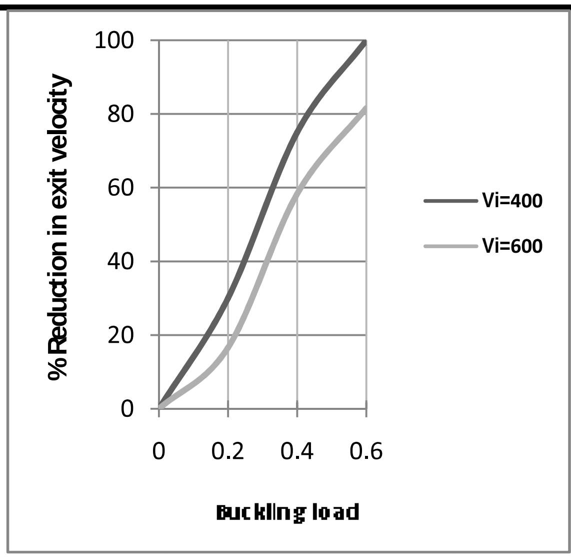

Figure 6-1 The percentage of improving in target resistance to penetration

6.1.4 Bulge height and radius of penetration zone

Table 6-3 The maximum bulge height and maximum radius of penetration

State of structure	V_i m/s	Max. bulge height mm	Max. radius of penetration mm
No compression	400	10	16
	600	10	16
Biaxial compression $F_x=F_y=0.6F_{Buckling}$	400	25	40
	600	35	50

Figure 6-2 The penetration shape at no compression.

Figure 6-3 The bulge height for biaxial compression case ($F=0.6F_{Buckling}$) at V_i = 400 m/s

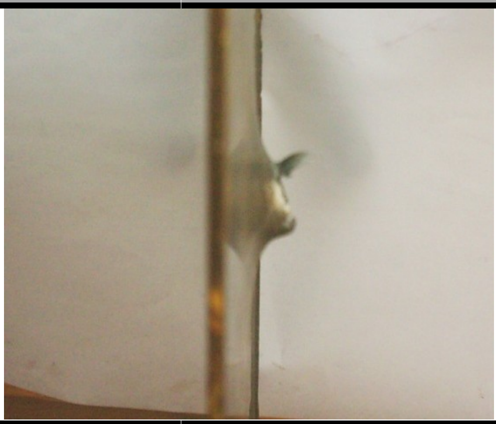

Figure 6-4 The bulge height at biaxial pressure case ($F=0.6F_{Buckling}$) at V_i =600 m/s

6.2 Theoretical results

Table 6-4 Exit velocity for different cases

state of structure	Impact velocity m/s	Exit velocity m/s	% reduction in exit velocity
No compression	400	342	14.5
	600	551	8.16
$F_x=F_y=0.6F_b$ $0.6F_{buckling}$=32.2 kN	400	46	90
	600	180	70

6.3 Comparison of the results

Table 6-5 Results of exit velocity

State of structure	Impact velocity V_i m/s	Experimental		Theoretical	
		exit velocity V_o m/s	% reduction in exit velocity	exit velocity V_o m/s	% reduction in exit velocity
No compression	400	351	13.85	342	14.5
	600	560	6.66	551	8.16
Biaxial compression at $0.6F_{Buckling}$	400	0	100	46	90
	600	110	81.6	180	70

6.4 Discussion

For the case where the target is under normal condition (no compression, it seems that the crack propagation within the target metal is instantaneous with no resistance or any confining measures against there crack propagation, then the amont of energy absorption is ineffective. however and due to the compression load imposed on the target, the resistance to penetration has noticeably increased due to the impeding of crack propagation due to the more condensed particles in the metal. For there same reasons the max bulge height and radius of penetration zone are effected and are as show in **(Table 6.3)**.

7. Conclusions

1. A target plate of specific thickness under normal condition has shown negligible resistance to perforation and penetration of steel projectile.
2. The same targets but under biaxial compression load (at $0.6F_{Buckling}$) has shown a tremendous improvement up to 82% its resistance to penetration and perforation.

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الخلاصة

إن أهمية تطبيقات ظاهرة التغلغل والاختراق في الأهداف في المجالين العسكري والمدني جعلت منه موضوعا لكثير من الدراسات والأبحاث ,ولكن أكثرية هذه الدراسات كانت تجريبية بسبب تعقد العلاقات الرياضية لوصف الظاهرة ولذلك فان اغلب النماذج التحليلية المتوفرة إما معقدة جدا أو مبسطة إلى درجة بحيث أنها تهمل الكثير من العوامل المهمة المؤثرة , هذا من جانب, ومن جانب أخر فان الوزن والكلفة هي من أهم العوامل المؤثرة في تصميم منظومات مقاومة الاختراق (دروع الاحتواء). وعليه فقد تركز البحث الحالي على دراسة ظاهرة تغلغل قذائف صلدة اسطوانية مخروطية الرأس لأهداف معدنية سميكة نسبيا ومعرضة لانضغاط أحادي الاتجاه في حالة وثنائي الاتجاه وقد بلغت قوة الانضغاط تقريبا 0.6 من حالة حصول الانبعاج. ولتحقيق الجانب العملي ثم بناء جهاز انضغاط خاص لهذا الغرض وتم كذلك استخدام عتاد حقيقي عيار 7.62 ملم مع رؤوس فولاذية مع تحقيق سرعة ارتطام مقداره 400 و600 م/ثا .بالإضافة إلى ذالك فقد تم اشتقاق نموذج تحليلي لحساب السرعة النفاذية (سرعة الخروج من الهدف) بدلالة سرعة الارتطام والشغل الكلي المنجز على الهدف وذلك في حالة كون الهدف معرض إلى انضغاط ثنائي الاتجاه. تبين من مقارنة النتائج النظرية والعملية بوجود تقارب جيد في هذه النتائج بالإضافة إلى وجود تحسن بنسبة حوالي ٨٠% في مقاومة الأهداف المعرضة لانضغاط إلى عملية الاختراق.