COMPARISON OF PERFORATION THEORIES AND SOME EXPERIMENTAL RESULTS

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Abstract In this paper it is shown that the variety of mathematical models proposed, such as Nishiwaki [1], Recht and Ipson [2], Lambert and Jonas [3], Awerbuch and Bodrer [4], Nixdorff [5] and the modified analysis given by the author in earlier papers [6], [7] almost all adhere to one basic form,

$$w_f^2 = \left\{ \begin{array}{ll} 0 & , \quad 0 \leq w_I \leq w_B \\ a(w_I^2 - w_B^2) & , \quad w_I > w_B \end{array} \right\} \tag{1}$$

This shows clearly the relationship between the striking velocity W_I, the residual velocity W_f, and the ballistic limit velocity W_B. It is also shown that in the case of modified analysis [6], [7] equation (1) may be easily applied to the preforation of double and multilayer targets. The computed results also shown a good correlation with experiments.

چکیده دراین مقاله نشان داده شده است که تعداد زیادی از مدل های ریاضی فرآیند نفوذ مانند نیشیو اکی [۱]، رشت و ایپسون [۲]، لمبرت و جونز در مرجع [۳]، آوربوخ و بودنر [۴]، نیکسدورف [۵] و تئوری اصلاحی لیاقت [۶]، [۷] را می توان بشکل رابطه زیر نمایش داد،

$$w_f^2 = \left\{ \begin{array}{ll} 0 & , \quad 0 \leq w_I \leq w_B \\ a(w_I^2 - w_B^2) & , \quad w_I > w_B \end{array} \right\} \tag{1}$$

رابطه (۱) ارتباط بین سرعت برخورد W_I، سرعت نهائی W_F و سرعت حد W_B را نشان می دهد. همچنین نشان داده شده است که درحالت تئوری اصلاحی لیاقت [۶] و [۷] رابطه (۱) را می توان به آسانی جهت تحلیل نفوذ در هدفهای دو لایه و چند لایه بکار برد. نتایج محاسبات، همخوانی خوبی با یافته های تجربی نشان می دهد.

INTRODUCTION

Impact damage to structures can be broadly related to three classes of targets, semi-infinite, finite and complex [8]. The semi-infinite target is defined as that for which there is no meaning either to a distal surface or to a ballistic limit or, in other words, a homogeneous material of thickness and size such that free surface effects will have negligible influence on the impact damage for a given impact condition. The finite target is one of such a thickness that the free surface effects will influence the impact damage. The complex target is composed of two or more targets, either laminated or spaced at a certain distance, with or without a filling medium between.

Laminated metallic plates and structures are increasingly being used in the electrical, chemical, aircraft industries and in armoured vehicles in the components designed for protection from the projectiles. The relative effectiveness of single plate targets and laminated targets has been studied in the past by a number of investigators such as Whipple [9], Ariska [10], Honda [11], Calder and Goldsmith [12], Zaid et al. [13], Ghosh and Travis [14], Shadbolt et al.[15], Marom and Bodner [16], Wong [17], Eleiche and Abdel-Kadar [18]. Mayseless et al. [19] and Liaghat [7]. But there is still a need for considerably more information in this area of terminal ballistics.

Compared with research into the penetration of single plate targets, only a limited amount of information has so far been published on the behaviour of multilayered targets subjected to ballistic impact conditions. The main reason for this lack of information is the complexity of the ballistic impact phenomenon in the case of multilayered targets. The complexity of the phenomena in these kinds of processes may require the conduct of additional investigations and more experimental results before a reliable and comprehensive analytical representation of the event can be considered.

In an earlier paper [6] the author suggested some modifications to the basic theory of Awerbuch and Bodner [4] that gave a much better correlation with the experiments in cases of ballistic impact of thick metal targets. Later he [7] showed clearly the relative merit and flexibility of the modified analysis [6] when Nixdorff's [5] suggestions of a possible relationship between the striking velocity W_I, the residual velocity W_f and the ballistic limit velocity W_B is incorporated to the modified analysis [6] and the simulated results compared with those given by Nixdorff [5].

The present work performed by the author and reported here shows that the above mentioned models [1,2,3,5,6] almost adhere to the basic form of Equation (1).

In this paper, some experimental results are also presented for the perforation tests performed by the author on multilayered aluminium targets and the results are compared with the analytical results of this paper and reference [5].

THEORY

For simplicity, the final form of the relationship between the striking velocity, "W_I" ballistic limit velocity, "W_B", and the final velocity, "W_f", proposed by the above investigators may be summmarised as follows:

(a) Nishiwaki [1]

$$W_f^2 = a(W_I^2 - W_B^2) \qquad (2)$$

where

$$a = \exp(-2\pi a^2 h \rho \sin^2\theta / M_o) \qquad (3)$$

and

$$W_B = \left\{ \frac{g\,Po}{\rho \sin^2\theta} \left[\exp(2\pi a^2 h \rho \sin^2\theta / M_o) - 1\right] \right\}^{1/2} \qquad (4)$$

where "g" is the acceleration of the gravity, θ is the projectile's nose angle and Po is the static contact pressure acting on the projectile and the other parameters have their own usual meaning ([1]).

(b) Recht and Ipson [[2].

$$W_f^2 = a(W_I^2 - W_B^2) \qquad (5)$$

$$a = [M_o/(M_o + M_{plug})]^2 \qquad (6)$$

and

$$W_B = \frac{4\Omega h^2 \psi \eta}{L_p D} \left\{ 1 + \left[\frac{L_p + \Omega h}{\Omega h}\left[1 + \frac{D}{4\rho h \eta \psi^2}\right]\right]^{1/2} \right\} \qquad (7)$$

Where L_p is the length of the projectile, H is the target's thickness, D is the projectile's diameter, ρ is the target's density and Ω, η and ψ are constants.

(c) Lambert and Jones [Ref [3], pp. 194, 196-202]

$$W_f^2 = \begin{cases} 0 & 0 \le W_I \le W_B \qquad (8) \\ a(W_I^Q - W_B^Q)/Q & W_I \ge W_B \qquad (9) \end{cases}$$

$$a = [M_o/(M_o + \rho A h)/3)]^2 \qquad (10)$$

$$Q = 2 + N/3 \qquad (11)$$

$$N = h/D \sec^{0.75}\theta$$

$$W_B = C_b \left[\frac{L_p}{D}\right]^{0.15} (f(N) D^3/M_o)^{1/2} \qquad (12)$$

$$f(N) = [\,1 + h/D \sec^{0.75}\theta + \exp(-h/D \sec^{0.75}\theta)] \qquad (13)$$

and C_b is a constant depending on the target material, h, D and θ are defined earlier.

(d) Awerbuch and Bonder [4], (suggested by Nixdorff [5]).

$$W_f^2 = a(W_I^2 - W_B^2) \qquad (14)$$

$$a=\left[\frac{M_o}{M_o+\rho A_2 h}\cdot\frac{M_o+\rho A_2(h-c)}{M_o+\rho A_1(h-c)}\right]^{2+k} \qquad 15)$$

and

$$W_B^2=W_{12}^2+\left[\frac{1}{a}\right]^{2+k}W_{3B}^2 \qquad (16)$$

W_B is the ballistic limit velocity, W_{12} is the ballistic limit velocity of the first and second stage and W_{3B} is the ballistic limit velocity of the third stage.

(e) Liaghat [7], (see also reference [6])

$$W_f^2=a\,(W_I^2-W_B^2)$$

where

$$a=\exp\left\{(-k\rho[A_{2C}C_2+A_{1C}(h-C_2)])/(M_o+\rho A_{2C}b_{2C}/4)\right\} \qquad (18)$$

$$W_B^2=W_{12}^2+\frac{1}{a}W_{3B}^2$$

Definitions of the above parameters are given earlier.

Application of the Above Analysis [7] to the Perforation of Double and Multilayer Targets -Nixdorff's Approach

Besides applying Equation 1 to the perforation of monolithic targets, it was found that this could be applied to the perforation of double and multilayer targets.

According to Nixdorff [5] for the double layer target if the subscripts 1 and 2 describe the first and the second layer of the target respectively, then for each layer Equation 1 has the following form,

$$W_{f1}^2=a_1(W_I^2-W_{B1}^2) \qquad (20)$$

and

$$W_{f2}^2=a_2(W_{f1}^2-W_{B2}^2) \qquad (21)$$

Equations 20 and 21 can easily be combined to yield.

$$W_{fD}^2=a_D(W_I^2-W_{BD}^2) \qquad (22)$$

where the subscipt D stands for targets made of double layers and,

$$a_D=a_1a_2 \qquad (23)$$

The ballistic limit velocity for the double layer target "W_{BD}" is then obtained as,

$$W_{BD}^2=W_{B1}^2+\frac{W_{B2}^2}{a_1} \qquad (24)$$

For multilayer targets with "n" layers a similar procedure to that given above can be followed and an equation similar to that for the double layer can be obtained.

$$W_{f1}^2=a_1(W_I^2-W_{B1}^2) \qquad (25)$$

$$W_{f2}^2=a_2(W_{f1}^2-W_{B2}^2) \qquad (26)$$

$$W_{fm}^2=a_2\,(W_{f(m-1)}^2-W_{Bm}^2) \qquad (27)$$

Combining Equations 25 to 27 it yields,

$$W_{fM}^2=a_M\left[W_I^2-W_{BM}^2\right] \qquad (28)$$

where, the subscript M stands for the multilayer targets and,

$$a_M=\prod_{j=1}^{n}a_j \qquad (29)$$

The ballistic limit velocity for the mulutilayer targets "W_{BM}" is,

$$W_{BM}^2=\sum_{j=1}^{n}\left[\frac{W_{BJ}^2}{\prod_{k=o}^{j-1}a_k}\right] \qquad (30)$$

where, for the sake of convenience $a_0=1$

RESULTS AND DISCUSSION

(a) Theoritical Considerations

As given above, all of the mentioned penetration theory adheres to the basic form of Equation 1. However, the particular value of slope "a" and the balistic limit velocity

"W_B" given for each theory differ from each other, except in the case of the modified analysis given by the author [7] and the analysis of Nishiwaki [1], which might be made to fit together by some small modifications to Nishiwaki's theory.

Comparison of Equations 3 and 18 given for the slope "a" the two theories of Nishiwaki [1] and Liaghat [7] also shows that they are almost the same. Both equations given for the slope "a" are in exponential form. The numerator in the argument in Nishiwaki's Equation 3, ($\pi a^2 h\rho$), gives the mass of the plug ejected from the plate and M_0 in the denominator is simply the mass of the projectile. In the case of the modified analysis also, Equation 18, the sum of both terms in the numerator, $\rho\,[A_{2c}C_2+A_1c(h-C_2)]$ gives the mass of the plug and the denominator of Equation 18 gives the mass of the moving body. The term k in Equation 18 is the projectile shape factor and is equal to $\sin^2\theta$ which is also present in Nishiwaki's Equation 3. Therefore, it can easily be seen that the values of slope "a" for both analysis approximately agree.

(b) Experimental Observations

Perforation of Multilayer Targets Made of Layers of Equal Thickness

A series of perforation tests were performed on the multilayer targets made from individual layers of thickness, t = 3.175mm, 4.725mm and 6.35mm, with the different number of layers, n = 1,2,3,4,5 and 6.

In the multilayer target plates made of thinner layers (individual layers of thickness h = 3.175mm) a plugging mode is usually observed in the first two layers and almost all the layers that are penetrated after these layers are perforated in the petalling mode (see Figure 1). This is primarily due to bulging and enlargement of the holes in subsequent layers due to the intense pressure exerted by the front layers on those at the back. Another interesting point observed was that for targets made of thin layers, when the numbers of layers increased to more than 4 or 5, the petals of the front layers, ie. the third or fourth layer, etc., were stretched and were pushed into the back layers. It is also worth nothing that for the plugging mode of the first two layers, the diameter of the plug of the second layer is usually smaller and its thickness is greater that that of the plug from the first layer. This is due to the greater compression exerted on the first layer.

For targets made of thicker layers (h=4.725mm), usually a plugging mode is observed up to the third layer. In this case also, the diameter of each of the plugs obtained from the layers decreases from layer to layer. In the case of multilayer targets made of relatively thick layers (ie. 6.35mm), it was also possible to observe a plugging mode up to the third layer. Detailed observations made from the perforated targets showed that usually the first layer had no deformation (ie. bending): this was probably due to the impact on it of the maximum velocity of the projectile and the layer behaved in a somewhat similar way to that of a single layer target. However, the subsequent layers showed more deformation. This was mainly dut to the following two reasons; firstly, the penetrated layer interacted with the other back-up layers and, secondly, the build-up of the plug material on the projectile tip from the previously penetrated layers pushed the back-up layers apart. As the projectile entered more and more into the inner layers (later layers), it pushed some of the target material from the previous layers (excepting the plug) around the circumfer-

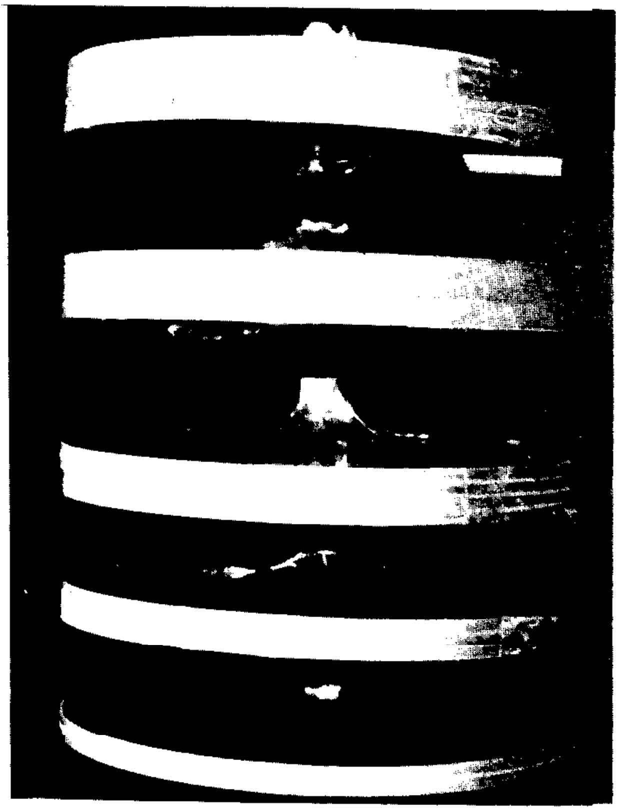


Figure 1. Photographs of perforated multilayer targets of individual layers of thickness 3.175 mm. Approximate initial velocity W= 600 m/s.

ence of the hold into the inside of the later subsequent layers. This pushed the target material circumferentially around the projectile and caused additional friction between the material from the previous layer and the current perforated layer. Figures 1,2 and 3 show the views of the perforated 2 layer, 3 layer, 4 layer, 5 layer and 6 layer targets made up of 3.175mm thickness each, and 2 layer, 3 layer, 4 layer targets made of 4.725mm thickness each, and 2 layer and 3 layer targets made of 6.35mm thickness each, respectively.

Figures 4 (A) and (B) show the plots of the theoretical and the experimentally observed results for the residual velocities (in the form of velocity drop of the projectile $(W_I-W_F)/W_I$) and ballistic limit velocity (in the form of $(W_I-W_B)/W_I$ versus the total thickness of the target material respectively. Comparing the theoretical and experimental results, it is observed that good agreement between the two exists for targets made of 2 layers for the 3 types of thicknesses of the individual layers 3.175mm, 4.752mm and 6.35mm, say A, B and C respectively. The agreement is satisfactory up to 3 layers but after the three layers the results diverge from each other. In each case the value of the residual velocities measured experimentally were always found to be less than the corresponding theoretical results. Most probably, this is due to the neglect of the effect of changes in the overall geometry and of the deflection of each individual layer of plate in the analysis.

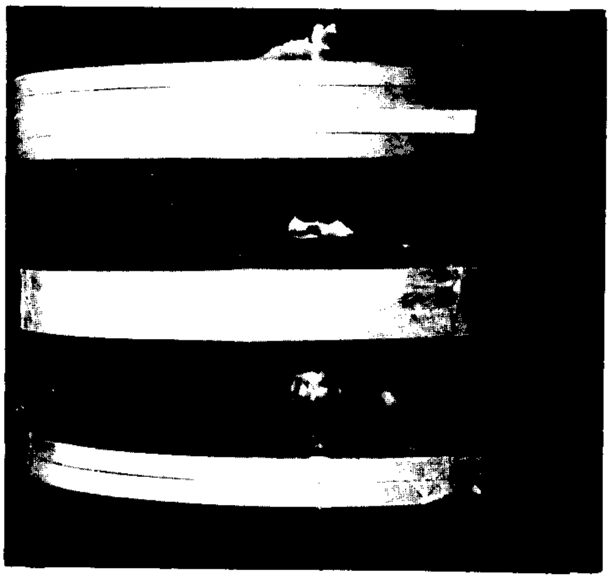
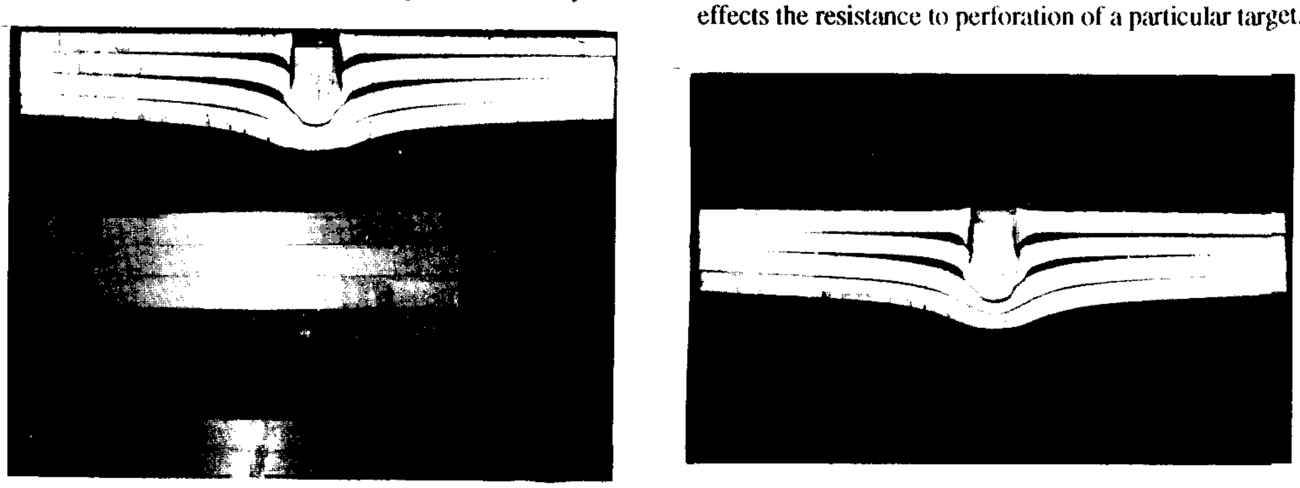


Figure 2. Photographs of perforated multilayer targets of individual layers of thickness 4.725 mm. Approximate initial velocity W= 600 m/s.

In addition the effect of the back-up layers on the layer in front is of some significance. For a correct analysis of the problem, this aspect of the problem (ie. the effect of the back layer) must also necessarily be considered in the analysis of multilayer targets. A difficult problem in the investigation of the perforation of multilayer target plates is the interaction between overall structural deformation and the localized mechanism of perforation which in turn effects the resistance to perforation of a particular target.



Deformed targets

Cross Sectic

Figure 3. Photographs of Cross section and deformed multilayer targets. (a) Incomplete Perforation of multilayer targets Consisting of 4 largers of 4.725 mm of 6351-TF alloy. (b) and (c) Targets with three and two layers of 6.35 mm of 6351-TF Aluminium allay.

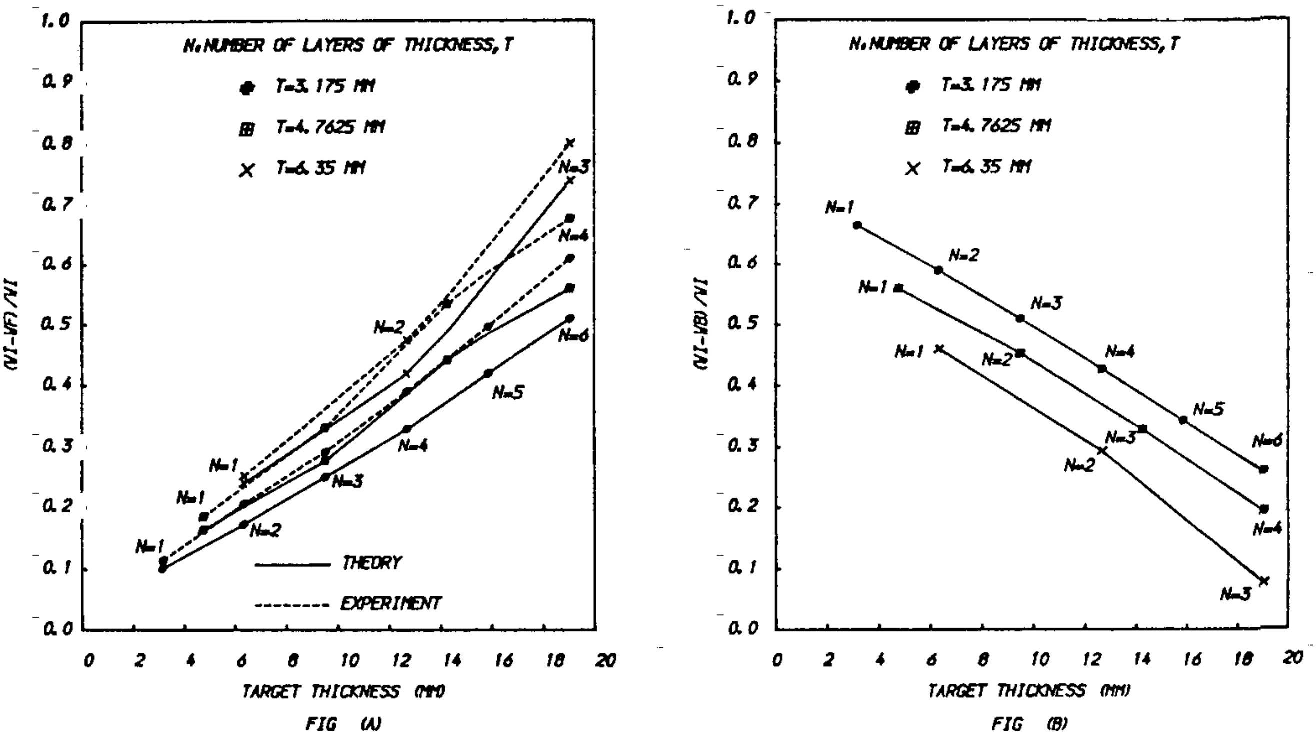


Figure 4. Dependence of residual, and ba listic LIMIT velocity on the total thickness.

In a just-in-contact multilayer target, the downstream layers would have a great influence on the perforation of the current impacted layers and generate an additional resistive force on the projectile-plug system and therefore an additional work term should be considered in the energy balance equation.

Perforation of Multilayer Targets of the Same Total Thickness Made of Different Thickness of Individual Layers. (A Comparison of the Theoretical Results and the Experimental Observations)

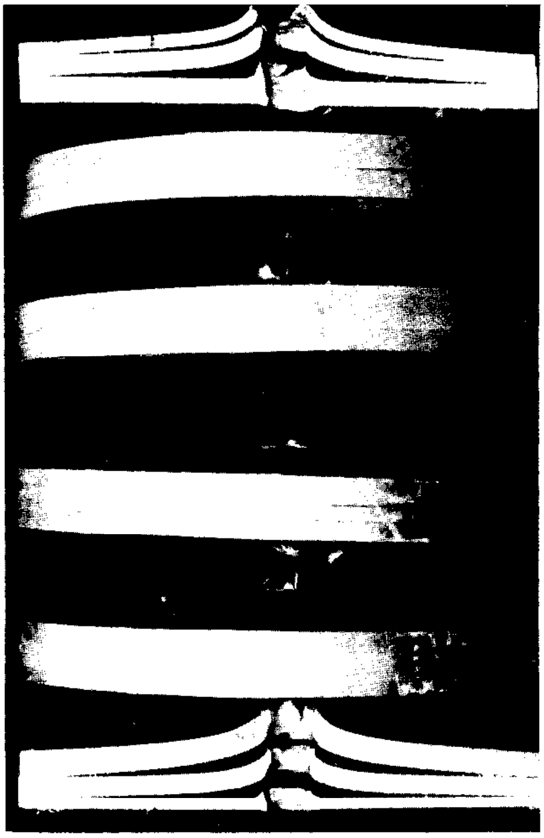
A second series of multilayer perforation tests on the targets made of 3 layers where each layer A, B and C had different thicknesses were performed. The order in which A, B and C were placed in front, in the middle, and at the back, was changed as shown in Figures 5 and 6.

The results of the experimental observation and the theoretical work based on the author's analysis [7] are shown in Figures 7 (a) and (b) where the arrangement of the individual layers is also shown. These figures show the dependence of the residual velocity and the ballistic limit velocity on the ratio of $(h_1+h_2)/h$, h_1/h and h_3/h, where h_1, h_2 and h_3 (or T_1, T_2 and T_3) are the thicknesses of the first, second are third layer and h (or T) is the total thickness of the target.

In the perforation of these multilayer targets, usually the plugging mode was observed in all three layers when the layers are just in contact. This was also observed when the layers are spaced and the thinnest layer faces the firing side and the thickest is at the back, ie. ABC when $h_A<h_B<h_C$ (see Figure 8). But when the thickest layer is in the front (firing side) and the order of different layers is from thick to thin, ie. CBA when $h_C>h_B>h_A$, petalling occurs in the third layer.

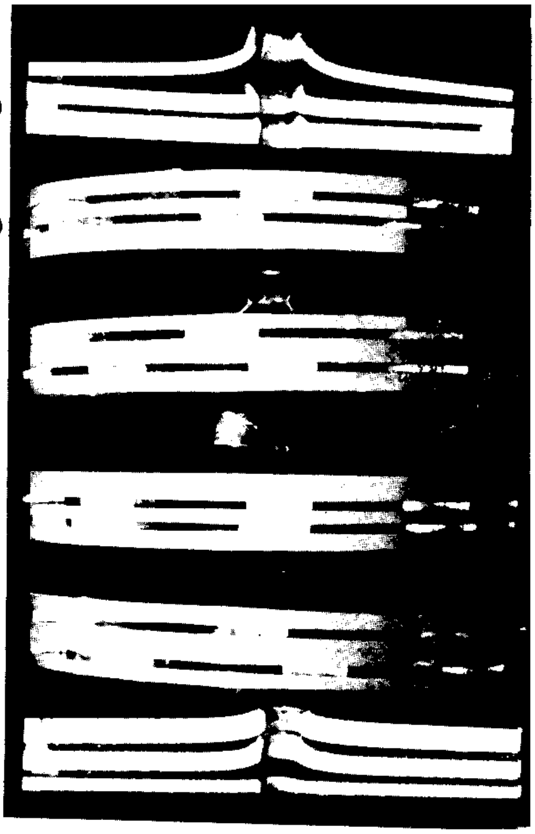
With regard to the structural plastic behaviour, it is noticed that in general the first layer does not show any significant plastic hinge movement or bending and perforation in the plugging mode. In the second layer, bending of the plate is often observed. In the third layer bending of the plate is clearly observed and this is the case for almost all of the configurations and thicknesses of the targets explored.

Comparing the results shown in Figures 7(a) and (b), it is observed that the variation in the theoretical and the experimental results for the residual velocities are in the same sense and in the case of spaced layers are in very good agreement. This is clearly encouraging and shows that the method of numerical simulation adopted intially as a comparison with the experimental work for the same



(a)
(b)
(c)
(d)
(e)
(f)

Figure 5. Photographs of the just in contact multilayer targets consisting of three layers of different thicknesses.
Layer sequence are:
(a) CBA, (b) CAB (C) BCA
(d) BAC, (e) ACB (f) ABC
Where thickness of A= 3.175 mm,
B= 4.725 mm, C= 6.35 mm.



(a)
(b)
(c)
(d)
(e)
(f)

Figure 6. Photographs of the spaced multilayer targets consisting of three layers of different thicknesses. Layer sequence are:
(a) CBA, (b) CAB, (c) BCA
(d) BAC, (e) ACB, (f) ABC
Where thickness of A= 3.175 mm,
B= 4.725 mm, C= 6.35 mm.

thickness layers can be used for designing multilayer targets made of different thickness layers in various configurations whenever a particular application is desired. Results of the experimental and theoretical work shown in Figure 7 indicate clearly that the maximum resistance to perforation is achieved when the relative target thickness of the first two layers $(h_1+h_2)/h$ is the highest. This occurs when $h_1>h_2$ and $h_2>h_3$. On the other hand, the resistance offered by the multilayered target is a minimum when $(h_1+h_2)/h$ is the least, ie. when $h_1<h_2$, $h_2<h_3$. This is most probably due to two reasons: first, the numerical calculations showed that the decrease in the slope "a"

$$a=\prod_{i=1}^{m} a_i$$

depends greatly on the increase of such parameters as A_{1C}, A_{2C}, h and C_2 for each of the individual layers. If the thicker layer is struck first, "a", is low and the flattening of projectile is also greater when the projectile reaches to the second layer (thinner one); this causes the slope "a_2" for the thinner layer, which is at the back of the thicker layer, to be lower than if the thinner layer was on the firing side. This can also be explained on the basis of the experimental observation. As the projectile penetrates the second layer, instead of being flat ended, it now has a plug from the material of the first layer in front of it which moves with it, so that it is more deformable and causes A_{1C} (current area at the first stage) for the next layer to increase and therefore to decrease the slope "a" thus decreases the residual velocity. Secondly, having the more deformable projectile (because of the plug in front of the projectile) also causes a large bulging of the subsequent layers and this dissipates

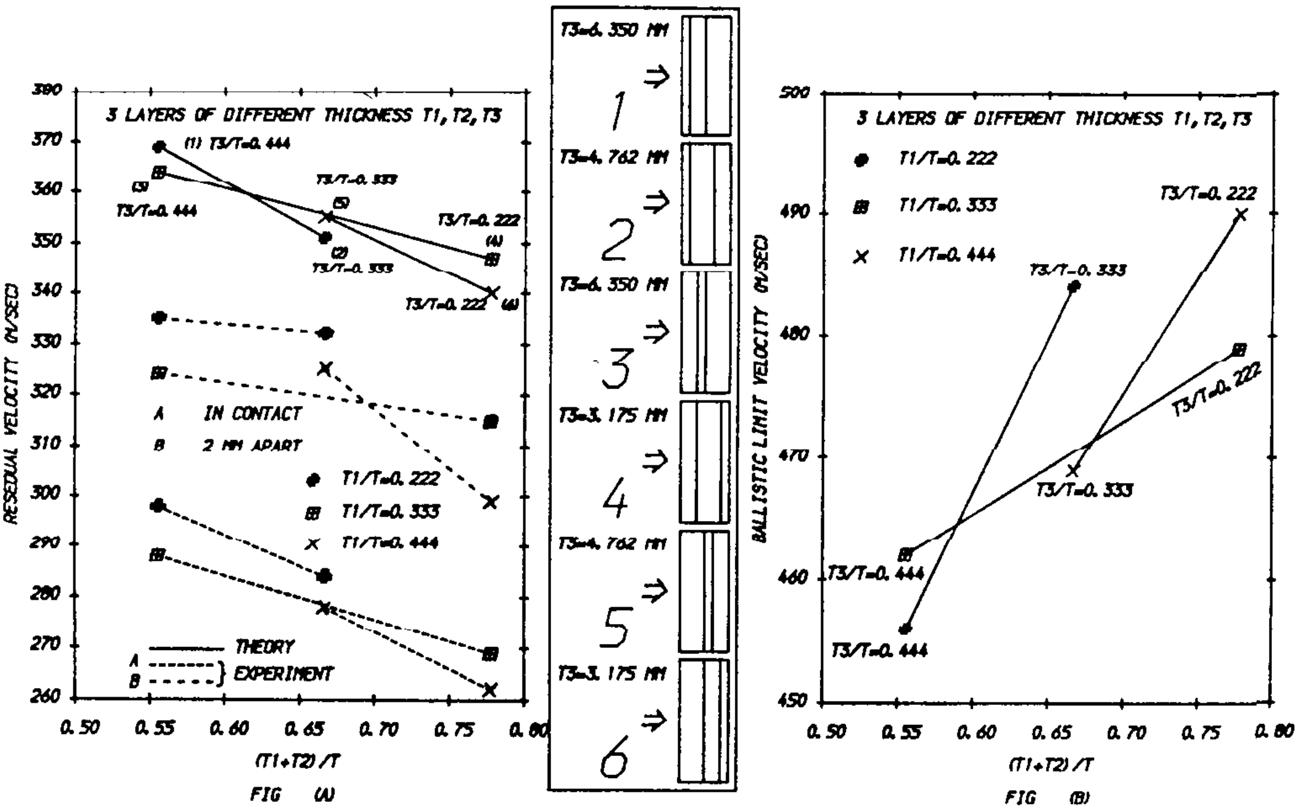
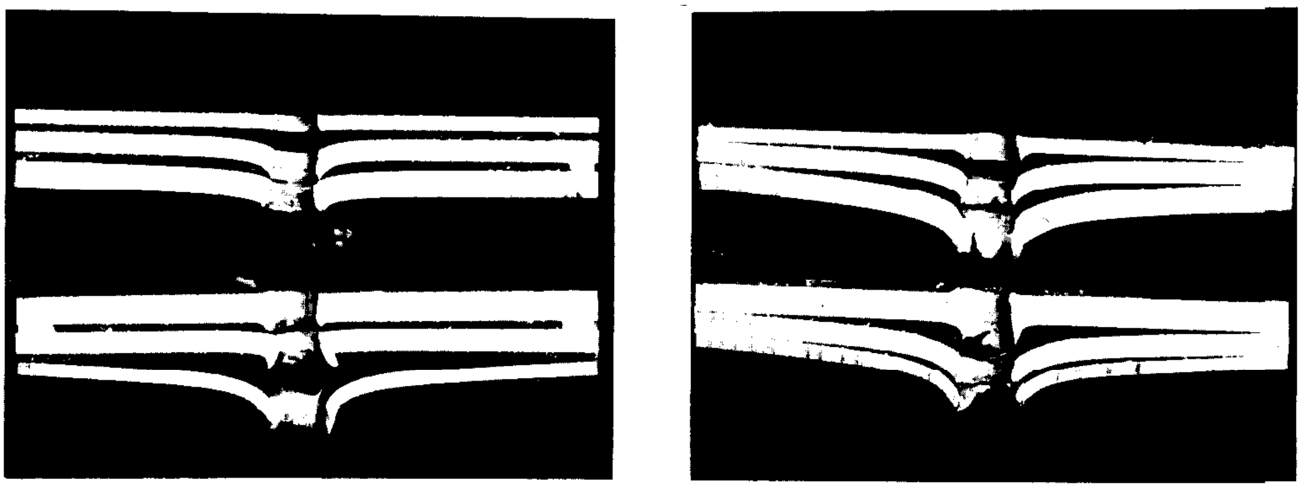


Figure 7. Dependence of residual, and Ballistic Limit Velocity on the Ratio of, (T1+T2)/T, T1/T, T3/T.



Spaced layers

Just in Contact layers

Figure 8. Photographs of Cross Section of the perforated just in contact and spaced multilayer targets. (a) Layers sequence ABC(A in firing side), (b) Layers sequence CBA (C in firing side) Where thickness of A= 3.175mm, B= 4.725mm, C= 6.35mm.

more energy from the projectile. Therefore, placing the thicker layer first and the thinner layers at the back reduces the slope "a" and thus the final (residual) velocity.

CONCLUSIONS

From a series of experimental and numerical studies made during the course of this investigation, the following conclusions may be made:

(1) The above mentioned theories ([1], [2], [3], [5], [6]) adhere to the basic form of equation (1), and this can be applied to double or multilayer targets.

(2) For a constant thickness target made up of different layer thicknesses better ballistic resistance is obtained when the order in which the individual layers are placed is thick to thin, ie. the thickest layer placed first in the firing side.

(3) The theoretical prediction based on the analysis of this paper for those cases when the layers in the multilayered targets are spaced, are in good agreement with the experimental results observed in the test program and, in the case of the multilayered targets when the layers are just in contact with each other, the agreement between the experimental and theorectical results are poor,but still significantly better than Nixdorff's theorectical predictions.

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