THE BALLISTIC PENETRATION OF THIN FIBREGLASS PLATES

G N NURICK AND S R CRAWCOUR

UNIVERSITY OF CAPE TOWN
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G N Nurick and S R Crawcour

Department of Mechanical Engineering
University of Cape Town

ABSTRACT
An investigation into the ballistic penetration of thin fibreglass plates is presented. Experiments were performed using two different projectiles - blunt nosed and 30° conical, fired from a pressurised gas gun. Targets, made of E Glass in the form of chopped strand mat, were nominally of diameter 190mm and thickness from 1mm to 5mm. The speed of the projectile ranged from 20ms\(^{-1}\) to 70ms\(^{-1}\) and the projectile mass was 35 grams.

An existing theory for metallic plates using energy considerations was modified to predict the behaviour of fibreglass. This first approximation of the modified prediction compared reasonably well with the experiments, for both monolithic and layered targets.

INTRODUCTION
Shielding of equipment and personnel to prevent damage by high velocity impacts is a major concern in civilian and industrial applications. The response of the plates subjected to various loading conditions has been reported by many authors - for example, for impulsive loading (see Nurick and Martin [1,2]) and for projectile loading (see Liss et al [3], Radin and Goldsmith [4], Marom and Bodner [5]). These investigations have been primarily concerned with metal plates. Different material properties and cost considerations indicate the need for an awareness for using new materials. Fibreglass is considered a 'new' material and in its different forms, it can be compared favourably with steel for some mechanical properties, as shown in Table 1. Labor and Bhatia [6] investigated the response of graphite - epoxy laminates, using a drop tower and a gas gun to determine the impact resistance of various laminates. This was measured by the amount of damage of the laminate after impact.
This paper presents the experimental results of the penetration on thin fibreglass plates by flat- and 30° conical-nosed projectiles, and compares these results with those obtained for aluminium plates. An analysis for aluminium plates reported by Radin and Goldsmith [4] which incorporates a theory of energy balances to predict the behaviour of plates during impact by flat- and conical nosed projectiles is adapted to accommodate the fibreglass material.

THEORETICAL ANALYSIS

To model the fibreglass, an existing theory for metallic plates is adapted with various assumptions to accommodate the fibreglass properties. The theory used is that of Radin and Goldsmith [4], based on work by Recht and Ipson [7] and Marom and Bodner [5].

BALLISTIC LIMIT AND WORK OF PERFORATION FOR NORMAL IMPACT OF A FLAT-NOSED PROJECTILE ON LAYERED TARGETS OF THE SAME MATERIAL

The ballistic limit of multi-layered targets composed of the same material struck at right angles by a flat-nosed non-deformable bullet can be estimated from an energy balance that neglects the interaction term between layers. The work required to perforate such a structure, $W_{LT}$, is the sum of the work required to pass through each plate, $W_i$:

$$W_{LT} = \sum_{i=1}^{n} W_i$$  \hspace{1cm} \ldots(1)

(n = number of layers)

The work required to penetrate the rear plate, $W_R$, is determined experimentally at the corresponding ballistic limit from an expression that describes the arrest of the projectile in this component, given by:

$$W_R = \frac{1}{2} m_B \left( v_{BL}^E \right)^2$$  \hspace{1cm} \ldots(2)

where $m_B$ is the mass of the projectile and $v_{BL}^E$ is the ballistic limit from experiments.
The energy consumed to penetrate the frontal plate should include the work performed on the supporting layers during plugging, $W_{SC}$. When the energy balance of Recht and Ipson \[7\] is modified to account for this term, the result is:

$$(1/2)m_{BT}v_0^2 = E_{DH} + W_{SC} + 1/2(m_{BT} + m_p)v_r^2 \quad \ldots (3)$$

where $m_{BT}$ is the total mass of the striker and plugs from the previous layer, $E_{DH}$ is the energy required to deform the target and account for heat effects, $m_p$ is the mass of the plug and $v_r$ is the residual velocity. The term $E_{DH}$ is the difference between the initial and final kinetic energy, given by:

$$E_{DH} = 1/2(m_{pf} / (m_{BT} + m_{pf}))m_{BT}v_0^2 \quad \ldots (4)$$

where $m_{pf}$ is the free mass of the plug and $v_0$ is the initial velocity. At the ballistic limit $v_0 = v_{BL}$, where $v_r = 0$, equations (3) and (4) provide the expression for the work required to overcome the resistance due to the presence of the shear zone and compression of the supporting layers \[5\]:

$$W_{SC} = 1/2(m_{BT}(m_{BT} + m_{pf})m_{BT}(v_{BL}^1)^2 \quad \ldots (5)$$

where $v_{BL}^1$ is the ballistic limit for a frontal layer which cannot be calculated directly. However, $W_{SC}$ can be evaluated as the energy transmitted to the current layer through the peripheral shear zone $W_S$ and that transmitted to the supporting layers by compression $W_C$:

$$W_{SC} = W_S + W_C \quad \ldots (6)$$

The quantity $W_C$ produced by the compressive stress during plugging is:

$$W_C = 1/4 (\sigma_{UC} \pi d^2 T^1) \quad \ldots (7)$$

where $\sigma_{UC}$ denotes ultimate compressive strength, $d$ is the plug diameter and $T^1$ is the thickness of the frontal layer.
Marom and Bodner [5] assumed that the energy transmitted to the present layer in a multi-layered system by peripheral shear effects is the same as that for an isolated layer. Thus, $W_S$ is obtained from the energy balance of such a layer when $v_r = 0$ as:

$$W_S = \frac{1}{2}(m_{BT} / m_{BT} + m_p) m_{BT} v_{BL}^2$$  \hspace{1cm} (8)$$

where $v_{BL}$ is the ballistic limit of this isolated layer. Substitution of equations (7) and (8) into the energy balance, equation (3), yields:

$$v_r = (m_{BT} / m_{BT} + m_p) \left( v_0^2 - (v_{BL}^1)^2 \right)^{1/2}$$  \hspace{1cm} (9)$$

where the ballistic limit of the current layer is given by:

$$v_{BL}^1 = \left( v_{BL}^2 + \left( aCTTd^2T1 m_{BT} + mp \right) / 2m^2BT \right)^{1/2}$$  \hspace{1cm} (10)$$

This ballistic limit of the frontal layer accounts for the effects of the structural motion by inclusion of a peripheral shear energy term which is transformed into kinetic energy of the layer.

To evaluate equation (10) it is necessary to obtain the ballistic limit of an isolated layer from the experimentally determined ballistic limit of a homogeneous target of identical thickness, and from the measured dimensions of the plug from the frontal layer. The impact velocity on the rear plate is equal to the residual velocity after penetrating the adjacent frontal plate.

Hence, the impact velocity $v_0$ on the rear plate, i.e. the residual velocity after penetrating the n-1 adjacent frontal layers, equals its experimental ballistic limit only when the initial striking speed on the system is equal to the ballistic limit of the combination:

$$(v_r)_{n-1} = (v_0)_n = (v_{BL})_n$$  \hspace{1cm} (11)$$

The same procedure can be used to calculate the impact velocity for the n-1 adjacent frontal layers so that, finally, the required impact velocity on the first layer to provide the ballistic limit for the system can be calculated.
The assumptions made for this work are:

i) The plug formed by the projectile has a perfect circular shape and thus \( d \), the plug diameter, is taken as being equal to the projectile diameter.

ii) \( m_p \), the mass of the plug, was calculated using the ideal dimensions of the plug and the density of the fibreglass.

iii) Each layer is affected separately and has no influence on the adjacent layer.

Equation (10) was also used to determine the ballistic limits of the monolithic plates of various thicknesses. In this case, \( v_{BL} \) was put equal to zero.

**BALLISTIC LIMIT AND WORK OF PERFORATION FOR NORMAL IMPACT OF A CONICAL-NOSED PROJECTILE ON LAYERED TARGETS OF THE SAME MATERIAL**

The same approach in tracing the velocity drop through a succession of adjacent layers, can be used, with the modification that the residual velocity must be adapted to the different tip shape. Using the energy approach, the following equation can be obtained:

\[
v_{BL} = \left( \alpha_Y \left(2 + \frac{L_N^2 \tan \theta}{b}\right)/2\rho_t b \right)^{1/2} (L_N \tan \theta) \quad ...(12)
\]

where

- \( L_N = \) nose length
- \( b = \frac{m_B}{\rho_t} \Pi T \)
- \( \theta = \) half-cone angle
- \( \sigma_Y = \sigma_{UTS} \) for fibreglass

Equation (12) was used in determining the ballistic limit for layered targets, and for monolithic targets of various thicknesses, the following equation was used:

\[
v_{BL} = 0.83 \Pi T (1 + K^*) \left( D \sigma_Y / m_B (2 + K^*) \right)^{1/2} \quad ...(13)
\]
where $D = \text{Projectile diameter}$

$K = \pi p_t T a^2/3m_B$

$p_t = \text{target density}$

$a = \text{length of crack generated by the conical tip which is taken as 80\% of } D$

**EXPERIMENTAL APPARATUS AND PROCEDURES**

Experiments were performed using plate specimens of chopped strand glass mat laminate in accordance with SABS 141-1971 which exhibits the mechanical properties shown in Table 2. The target area was of diameter 190mm, and tests were carried out on plates of 1, 2, 3, 4 and 5mm thickness.

Two projectiles were used, blunt-nosed and $30^\circ$ conical (semi-apex angle) made from high strength steel and case hardened to Rockwell 'C' 60. Both projectiles were of identical volume and mass of 35 grams each. These are shown in Figure 1. These projectiles were fired from a pressurised gas gun and the projectile velocity just before impact was measured by means of two infra-red beams. The general layout of the experimental rig is shown in Figure 2.

The objective of this study was to investigate the penetration problem in order to obtain the ballistic limit. Figures 3 and 4 show typical terminal configurations for ballistic limits on fibreglass plates. The plate subjected to the flat-nosed projectile exhibits a distinct, although irregular plug, while for the plate subjected to the conical-nosed projectile, the formation of petals is illustrated.

In Table 3, the results of the ballistic limits of single and layered targets are given. Figures 5-10 show these results in graphical form.

**MONOLITHIC/LAYERED TARGETS** - The comparison of monolithic with layered targets is shown in Figures 5 and 6. For both projectiles, the monolithic targets are more resistant to ballistic impact than the layered targets.
EXPERIMENTAL/THEORETICAL COMPARISON - Figures 7-10 show the comparison of the experimental results with the predicted results. For those plates subjected to the flat-nosed projectiles, the ballistic limit was predicted using Equation (10), while for those plates subjected to the conical-nosed projectile, the ballistic limit was predicted using Equations (12 and 13). In all cases, Figures 7-10, there is a reasonable correlation between the experimental and predicted results.

FIBREGLASS/ALUMINIUM COMPARISON - In Figure 11, the ballistic limits of monolithic and layered aluminium plates for flat and conical-nosed projectiles, (taken from Radin and Goldsmith [4]) is shown. These results demonstrate that the monolithic targets have a higher ballistic limit than layered targets, for both projectiles. The same observation is made for fibreglass plates in this investigation, as shown in Figure 12. A comparison of Figures 11 and 12 shows that Aluminium exhibits a higher ballistic limit than fibreglass. This comparison further shows that for aluminium, the conical-nosed projectile exhibits a higher ballistic limit for both monolithic and layered targets than the flat-nosed projectile. For the fibreglass, the inverse is true.

POST-IMPACT OBSERVATIONS - After impact, the plates were visually inspected, and a number of observations were made as regards circular and radial cracks, petal and plug sizes - as illustrated in Figures 13-17.

A) Monolithic Target -
   i) Flat-nosed projectile - see Figure 13. The circular cracks are evenly spread from the centre (point of impact) to the outside radius. These cracks are concentric and become more dense as the plate thickness increases. The radial cracks are very fine and fairly localised towards the centre. Irregular plugs occur due to the glass fibre in the plates.
   ii) Conical-nosed projectile - see Figures 14 and 15. The radial cracks become larger as the plates get thicker. For the thinner plates, the cracks are localised with a small display of circular cracks. The size of the petals increase as the plate thickness increases.
B) **Layered Target**

i) Flat-nosed projectile - see Figure 16. The circular cracks are very large and well-dispersed from the center to the outer radius, but become more localised towards the centre from the first to the last plate. Radial cracks are less noticeable, and are only localised towards the centre.

ii) Conical-nosed projectile - see Figure 17. Both radial and circular cracks get more dense and more localised from the first to the last plate. The petals are fairly regular and become larger from the first to the final plate.

When the layered configuration is not completely penetrated, the first plate exhibits the usual four petals, and the second plate which is only indented, displays a triangular configuration which suggests the possible formation of three petals. This observation is analogous to the metal plate response.

**DISCUSSION**

In Figures 5 and 6, it is illustrated that the monolithic targets exhibit higher ballistic resistance than the layered targets. Radin and Goldsmith [4] attribute this to the monolithic targets having a greater bending resistance than the layered targets. (A similar phenomenon occurs with layered plates, subjected to uniform impulsive loading, (Nurick and Milburn-Pyle [9]).) Corran et al [10] report that for thick metal plates (greater than 5mm) this phenomenon changes. No results for plates of thickness greater than 5mm were tested in this investigation.

The results for the monolithic plates exhibit a change in curvature at a thickness between 4mm and 5mm. Corran et al [10] reported distinct changes in curvature for various metal plates at a plate thickness of 4mm. They attributed this kink to a change from energy absorption to perforation by plastic deformation of the plate. For fibreglass plates, there is no plastic deformation stage and this kink effect is under consideration.
The experimental results and theoretical predictions show a fairly reasonable correlation, in view of the assumptions made in adopting the existing theories for the more complex fibreglass material. Of interest is that the prediction using the flat-nosed projectile overestimates the ballistic limit, while the prediction using the conical-nosed projectile is generally underestimated the ballistic limit.

As observed in Figures 11 and 12, the conical-nosed projectile exhibits a greater ballistic resistance than a flat-nosed projectile for aluminium plates. The inverse being true for fibreglass plates. A possible reason for this is that for metal plates, the energy required for the flat-nosed projectile to shear the plate is less than the energy required by the conical-nosed projectile to overcome the friction when penetrating through the plate. This concept is illustrated in Figure 18. For the fibreglass plates, the energy required for the flat-nosed projectile to overcome the shearing during plug formation is greater than that required to overcome the friction effects for the conical-nosed projectile.

This is attributed to the mechanical properties of the materials. The shear strength and the tensile strength of the fibreglass are notionally similar, about 90 MPa, while for aluminium, the tensile strength is approximately 50% greater than the shear strength - 186 MPa to 124 MPa respectively. [13]

The cracks that are observed during the post-impact examination of the plates are believed to occur due to the elastic and brittle behaviour of the fibreglass laminate. The cracks occur in the layers of resin in the laminate and the glass fibres prevent the laminate from shattering as would be the case for a ceramic material. The cracks that occur are similar to those observed by Mayseless et al [11] when investigating ceramic materials impacted by various projectiles.

**CONCLUSION**

Within the range of target thicknesses investigated, the monolithic targets have a greater resistance to ballistic impact than the layered configurations of equivalent thickness, for both projectiles used.

In addition, the adapted theoretical models compare reasonably well with the experimental results.
ACKNOWLEDGEMENTS
The authors are indebted to J Mayer for his assistance with the electronic equipment, A E Allan for providing the fibreglass targets and M A Batho, D Finlayson for their assistance with the gas gun.

REFERENCES


12. Fibreglass South Africa (Pty) Ltd., Reinforcement Products

Figure 1. Drawings of Projectiles

1. Compressed N cylinder  
2. Press. regulating valves  
3. Driver chamber  
4. Valve pressure reservoir  
5. Solenoid valve  
6. Velocity measuring device

7. Target holder  
8. Projectile catcher  
9. Bright mild steel bed  
10. 300 x 125 R.S.J.  
11. Sq. steel tubular legs  
12. Control panel

Figure 2. Schematic of Experimental Rig
Figure 3. Photograph Showing Ballistic Limit for the Flat-Nosed Projectile

Figure 4. Photograph showing Ballistic Limit for the conical-nosed projectile.
Figure 5. Exp. Results - Flat-nosed Projectile Monolithic and Layered Targets

Figure 6. Exp. Results - Conical-nosed Projectile Monolithic and Layered Targets
Figure 7. Monolithic targets - Flat-nosed Proj. Experimental and Theoretical Results

Figure 8. Layered targets - Flat-nosed Proj. Experimental and Theoretical Results
Figure 9. Monolithic Targets - Conical-nosed Proj.
Experimental and Theoretical Results

Figure 10. Layered Targets - Conical-nosed Proj.
Experimental and Theoretical Results
Figure 11. Monolithic and Layered Aluminium Plates Impacted by Flat- and Conical Proj.

Figure 12. Monolithic and Layered Fibreglass Plates Impacted by Flat- and Conical Proj.
Figure 13. Photograph showing circular and radial cracks of a monolithic target impacted by the flat-nosed projectile.

Figure 14. Photograph of a 2mm plate impacted by the conical-nosed projectile. (Note - the localised cracks.)
Figure 15. Photograph of a 5mm plate impacted by the conical-nosed projectile
Figure 16. Photograph of a layered configuration impacted by the flat-nosed projectile, illustrating that the circular cracks become more localised from the first to the last plate.

Figure 17. Photograph of a layered configuration impacted by the conical-nosed projectile, illustrating that the radial and circular cracks become more dense from the first to the last plate.
<table>
<thead>
<tr>
<th>Material Type</th>
<th>% Glass Fibre</th>
<th>Flexural Strength (MPa)</th>
<th>Flexural Modulus (GPa)</th>
<th>Tensile Strength (MPa)</th>
<th>Tensile Modulus (GPa)</th>
<th>Compressive Strength (MPa)</th>
<th>Ultimate Tensile Composition (%)</th>
<th>Impact Strength (kJ/Kg.f)</th>
<th>Thermal Conductivity (W/m.K)</th>
<th>Density (g/cm³)</th>
<th>Heat Distortion Point (°C)</th>
<th>Continuous Heat Resistance (°C)</th>
<th>Thermal Coefficient of Expansion (10⁻⁶°C⁻¹)</th>
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<td>11-17</td>
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<td>0-0.25</td>
<td>1.25-1.47</td>
<td>1.96-0.912</td>
<td>180-200</td>
<td>180-200</td>
<td>1.7-2.1</td>
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<td>70-140</td>
<td>10-14</td>
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<td>8-11</td>
<td>180-235</td>
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<td>0-0.25</td>
<td>1.25-1.47</td>
<td>1.96-0.912</td>
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<td>180-200</td>
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<td>10-13</td>
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<td>180-200</td>
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Table 1. Property Comparisons of Fibre Reinforced Plastics and Metals
Table 2 - Mechanical Properties of Chopped Strand Glass Mat Laminate.
(according to [8] - SABS 141-1971)

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<th>Property</th>
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<tr>
<td>Tensile Strength</td>
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<tr>
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<td>Compression Strength</td>
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<tr>
<td>Glass Content</td>
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Table 3 Experimental and Theoretical Data

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<th>Conical-Nosed</th>
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