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Ballistic protection mechanisms in personal armour

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High strength and high modulus fibres have revolutionised the design of lightweight armour, main fibre reinforced ballistic products are: ballistic helmets, vests, blankets and add-on car armour. Modelling of the ballistic properties of multi-layer fibre reinforced armour is still in the development stage, structural models that can be used to describe the penetration of such armour by deformable projectiles, and to design new armour, are not yet available. A simple model has been developed that can be used to calculated the performance of Dyneema armour against deformable bullets and FSPs. Most important in this model is that the number of input values is very small. For calculating the performance of Dyneema UD-based armour only two materials related parameters are required. Four projectile related parameters are needed. For non-deformable projectiles the number reduces to a single material related and two projectile related parameters.

1. Introduction

High performance polymeric fibres have met a warm welcome, right from their introduction on the market. The availability of materials with strength surpassing widely that of traditional construction materials, has stimulated the imagination of many. A large number of idea's for new applications or creative solutions to existing problems have been proposed. However no single application field has been revolutionised to such an extent as the field of lightweight armour. Lightweight armour is used in those situations wherein traditional armour (as steel and concrete) cannot be used because of weight limitations. Major application fields are: personal protection, armouring of vehicles, helicopters, patrol boats and transportable shelters (as command shelters). Present day state of the art lightweight armour is based on strong organic and inorganic materials; an overview of specific applications is given in Fig. 1.

High performance fibres used in ballistic products are characterised by: low density, high strength, and high energy absorption capability (Fig. 2), In ballistic products are used: glass fibres (S-and R-glass), aramid (Kevlar, Twaron), high performance polyethylene (HPPE) fibres (Dyneema, Spectra). Recently ballistic products based on PBO (Zylon) have been introduced on the market.

Intuitively it can be appreciated that the ballistic performance of a material depends on its capability to absorb energy locally, and to its capability to spread out energy fast and efficiently. From such general considerations it is inferred [1] that for fibre based (textile) armour the tenacity and elongation at rupture of the fiber and the sonic velocity in the fiber (related to its specific modulus) are most important.

The specific energy absorption capability is related to the specific (density related) breaking strength and the strain at rupture:

$$E_{sp} = 0.5\,\sigma_{rupt} * \varepsilon_{rupt}/\rho$$

The sonic velocity is the square root of the specific modulus:

$$V_s = \sqrt{E/\rho}$$

The ballistic potential of various polymeric fibres is shown in Figure 3, wherein the sonic velocity is plotted against the specific energy absorption capability of several polymeric fibres.

As can be seen from this figure, Dyneema has a very high score in these two properties. Given the rating shown above, is not surprising that Dyneema, high performance polyethylene (HPPE) fibres, are extensively used in ballistic applications like vests, helmets and

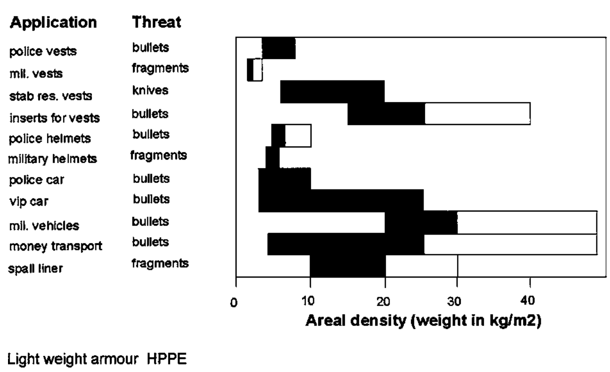


Figure 1 Light weight (HPPE) fibre reinforced armour, □ lightweight armour, ■ HPPE armour.

	Strength (GPa)	Modulus (GPa)	Elongation at rupture (%)
Aramid	2.8-3.2	60-115	1.5-4.5
HPPE	2.8-4.0	90-140	2.9-3.8
LCP	2.8	65	3.3
PBO AS	5.5	280	2.5
M5	4.0	330	1.2
S glass	4.65	87	5.4

Figure 2 High performance polymeric fibres.

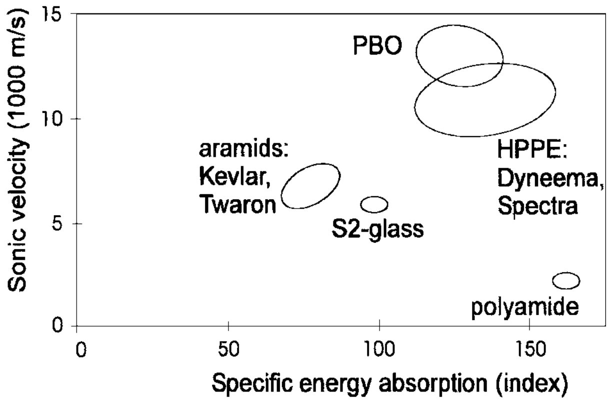


Figure 3 Primary ballistic figures of merit for various fibres.

armour panels. For such applications, personal armour or add-on armour on lightweight vehicles, the weight is crucial.

2. Modelling of the penetration behaviour of fibre based armour materials

While the basic ballistic potential of HPPE fibres is obvious, it has however proved to be very difficult to exploit the potential of these fibres fully in ballistic end-products, because a number of other factors, such as: fabric construction, areal weight of the layers, fibre to fibre and fibre to projectile friction, matrix, processing conditions, shape and mechanical properties of the projectile to be defeated, are involved.

Many efforts have been done for modelling the penetration behaviour of fibre reinforced armour, for example [2–7]. These models require a large set of parameters to be known and required sophisticated software. Such material models have not yet evolved to the stage where such models can be used for designing and optimising fibre reinforced armour, especially the effect of projectile deformation is difficult to implement. This means that a lot of research has to be done to find out what fiber type and what type of fabric, sheet or panel gives the highest protection level for the lowest weight. So far we needed a great deal of trial and error, helped by a growing practical experience but with a very limited theoretical support. For this research to be effective models of a phenomenological nature still have merit.

2.1. Dyneema UD based armour materials

A major step to improve the performance of the Dyneema fibres was to replace the woven fabrics by uni-directional layers of filaments. These layers are used in 0–90° constructions in the ballistic packet, see Fig. 4.

Using the same fibre grades, Dyneema UD gives a far higher protection level against the same projectiles

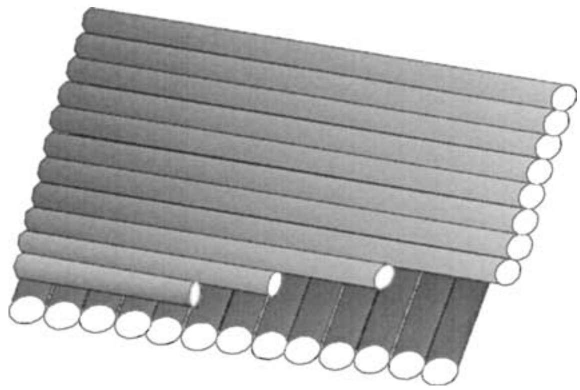


Figure 4 Scheme of Dyneema UD.

than woven fabrics. Very good results were obtained against handgun and rifle bullets using flexible 'soft' Dyneema packages and rigid 'hard' Dyneema panels. The improvement from fabric to Dyneema UD is explained by the wider area that responds to bullet impact. Because the shock wave that travels through fibres is not or less reflected against the yarn cross-overs that are ubiquitous in a woven fabric and that do not occur in the uni- directional product, the energy is distributed faster and more efficiently [8].

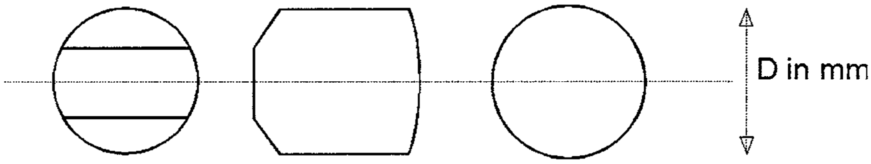
2.2. Penetration of non deformable fragment simulating projectiles (FSPs)

FSPs (Fragment Simulating Projectiles) do not deform on impact, so the ballistic behaviour is easier to predict than that from deforming bullets. Although the penetration of a multi-layer composite is a complicated process (7, 10), such detail is not required for predicting the power to stop a non-deformable projectile. In 1993 a model to predict the protection against FSPs was presented [9]. This model was based on our experience with V_{50} values against Dyneema (fabric based) armour using fragments of different sizes. The results of these test were that the energy absorption of a fragment is directly related to its strike face area (which has well defined relation with the weight of the fragment in the design according to Nato Stanag 2920). In the model the strike face area is the surface of the projection along the axis of the fragment. Fig. 5 shows the shape of the Nato FSPs. In Fig. 6, the relation is shown between the strike face area, the energy absorption and the density of the Dyneema ballistic package for fragments between 0.237 and 13.4 g.

The relation as shown in Fig. 6 has been approximated by (the dotted line):

$$E_{abs}/S = \mathrm{AD} \times c$$

with E_{abs} = absorbed energy in Joules, S = strike face area in mm^2, AD = areal density of the ballistic package in kg/m^2, c = ballistic material related constant, the slope of the curve. While it is obvious that there are systematic deviations from the linear fit, and that there is a systematic residual effect of fragment mass, the approximation is fair ($<10\%$ deviation) for those combinations of fragment mass and panel areal density



Weight (W) = 0.007 x D^3 in grams - Strike face area (S) = 1/4 x π x D^2 in mm^2

Figure 5 Nato FSP (Fragment Simulating Projectile).

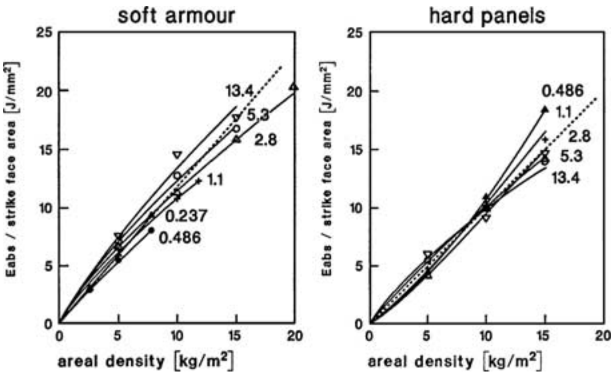


Figure 6 Normalised energy absorption versus areal density.

that are being used in practice. In this model the contribution of all the layers of the armour is the same. Only three parameters should be known for designing an armour against NATO FSPs: the mass and velocity of the projectile, and the ballistic material constant.

The model as described has been used successfully not only for predicting the performance of armours based on new fibre grades, but also for comparing the protection of different armour including steel armour, against fragments from a nearby exploding shell [6].

The FSP model presented is of a phenomenological nature, it does not provide an explanation of the ballistic results, but it has proved to be a reliable instrument to predict protection levels against fragments for woven fabrics and UD-based flexible and rigid armour.

2.3. Penetration by deforming bullets

Many bullets from hand guns and pistols will deform while being stopped in the armour. Examples are: .44 and .357 Magnum and 9 mm FMJ Parabellum (see Fig. 7). For deformable projectiles the model for FSPs cannot be used to calculate the relation between areal density and the V_{50}, because in this model the strike

Figure 7 Typical deformable bullets.

Figure 8 Cross-section of 21 kg/m^2 panel which has stopped a 7.62 Ball bullet impacting at 838 m/s Courtesy H. J. Iremonger (10).

face is constant and the contribution of each layer is the same.

In stopping a bullet, two additional aspects have to be considered: a change of penetration mode, and the deformation of the bullet. The first layers are penetrated without significant deformation of the projectile, the last layers are penetrated partially or not penetrated at all, and experience a high degree of deflection [10].

In the extension of the model to deformable projectiles it is assumed that after deformation the bullet again behaves as a non-deformable projectile, with a larger strike face. A model that can be used for predicting the V_{50} of Dyneema based armour was presented at the LASS Conference In Shrivenham 1999 [11].

The assumption on which the model is based are: the energy of the bullet is absorbed in three stages:

– first penetrating like an FSP with a low strike face area,
– deformation of the bullet, consuming kinetic energy
– further penetration or stopping of the bullet as a large area FSP.

The following parameter set must be available in order to use the model: the mass and the strike face of the projectile (not longer uniquely related), the strike face of the deformed projectile, the energy required for deformation of the projectile, and the position of the transition (for instance number of plies penetrated before the bullets starts to deform).

Questions to be answered: what is the strike face of e.g. a 9 mm Parabellum, what is the deformation energy of a bullet at ballistic velocities and where in the stopping process is the transition point. To solve these problems a large number of test results were analysed to find the best fit for these values. This resulted in a model that can predict V_{50} values for bullets like several types of 9 mm, Magnums, 7.62 Nato Ball and 7.62 AK47.

The first stage is penetration of the undeformed projectile. The bullet has a strike face area S_1, velocity V_1 and the corresponding kinetic energy E_1. The bullet penetrates part of the ballistic package with the areal density AD_1 and energy E_{abs1} is lost by the same mechanism as with an FSP:

$$E_{abs1}/S_1 = AD_1 \times c$$

In the deformation stage the bullet deforms instantaneously, a process wherein a fraction of its energy, E_{absB}, is absorbed. This energy is assumed to be constant for a given bullet and independent from the velocity. The larger strike face formed after the deformation has the area S_2.

In the third stage the bullet behaves again like an FSP but with the larger strike face area:

$$E_{abs2}/S_2 = AD_2 \times c$$

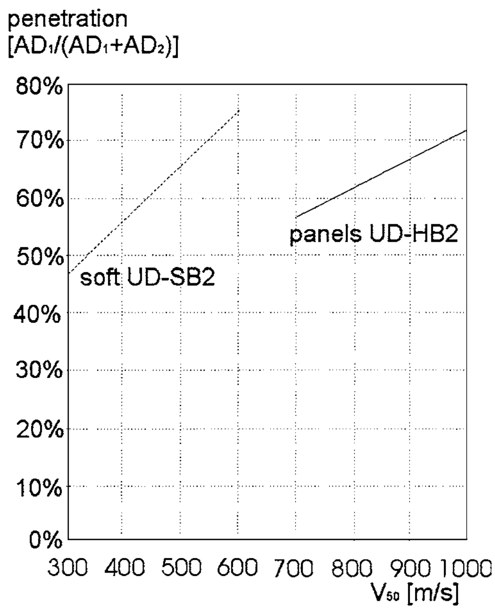


Figure 9 Percentage penetration of ballistic packages and panels.

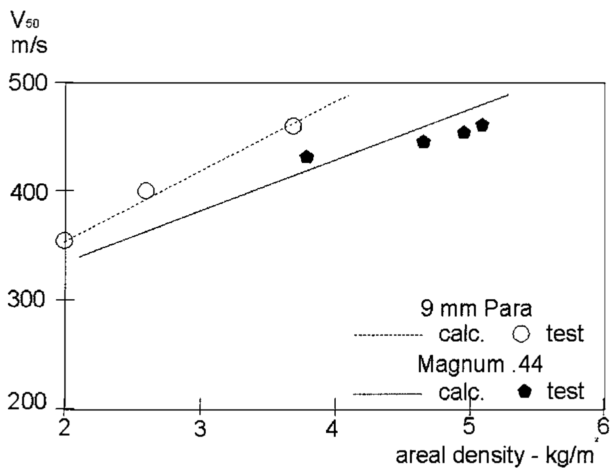


Figure 10 Calculated and measured V_{50} values in soft ballistic packages.

At V_{50} for the complete system the total kinetic energy of the bullet will be exactly consumed in the package. In the model the energy that remains after the two first stages, will also correspond with the V_{50} for the deformed bullet in the last part of the ballistic package. So:

$$E_1 = E_{\text{abs1}} + E_{\text{absB}} + E_{\text{abs2}}$$

In order to calculate for a bullet either the V_{50} at a given areal density or the areal density at a given velocity, one extra datum is needed. The two strike face areas can be measured, c is a material related constant (that can be measured using FSPs), the total energy absorbed in the three stages is equal to the kinetic energy and the sum of the areal densities AD_1 and AD_2 is the total areal density of the package.

What must be established is the transition point. It was found that for soft ballistics packages and hard (pressed) panels this relation is different. The percentage of the package that is penetrated before deformation starts, is shown in Fig. 9.

We tested these V_{50} respectively areal density calculations and found that the results were very good comparable with the tests of most bullets and most ballistic packages based on our Dyneema UD materials. However, one should bear in mind that establishing the V_{50} value of a textile based ballistic package is not a very accurate measurement.

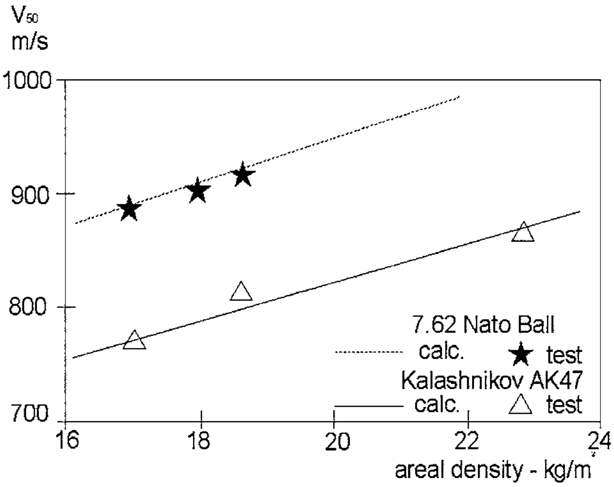


Figure 11 Calculated and measured V_{50} values in hard ballistic panels.

Dyneema	soft UD-SB2	hard UD-HB2		
c value	1.2	1.4		
Bullets	Initial strike face S_1 [mm^2]	Deformed strike face S_2 [mm^2]	Weight [g]	Deformation energy [J]
9 mm FMJ Para	55	225	8.0	160
.44 Magnum SWC	64	400	15.6	200
7.62 AK47 mild st.	65	200	8.0	300
7.62 Nato Ball	65	200	9.7	250

Figure 12 Input values for the V_{50} calculations.

3. Discussion and conclusions

Figs 10 and 11 show the calculated and measured V_{50} values. Fig. 10 shows two bullets, 9 mm Parabellum and Magnum .44, that are stopped with a soft Dyneema UD package against plastilin and in Fig. 11 the same for hard Dyneema panels for the rifle bullets 7.62 Nato Ball and for the same calibre Kalashnikov AK47 with a mild steel core.

The diagrams show a good agreement between calculated and measured values. Except with the 9 mm Parabellum, there is the restriction that most measurements are in a limited velocity range due to the fact the testing is mostly related to velocities that are asked by the common standards.

The input values used for the calculations are given in the table in Fig. 12. The c values shown are for soft Dyneema UD-SB2 and hard Dyneema UD-HB2, other grades will have another c value.

The initial strike face area S_1 for the bullets can not readily be seen from the bullet itself. The ballistic package will follow the form of the bullet to some extent so

Figure 13 Stopped 9 mm Parabellum bullet in a soft ballistic package.

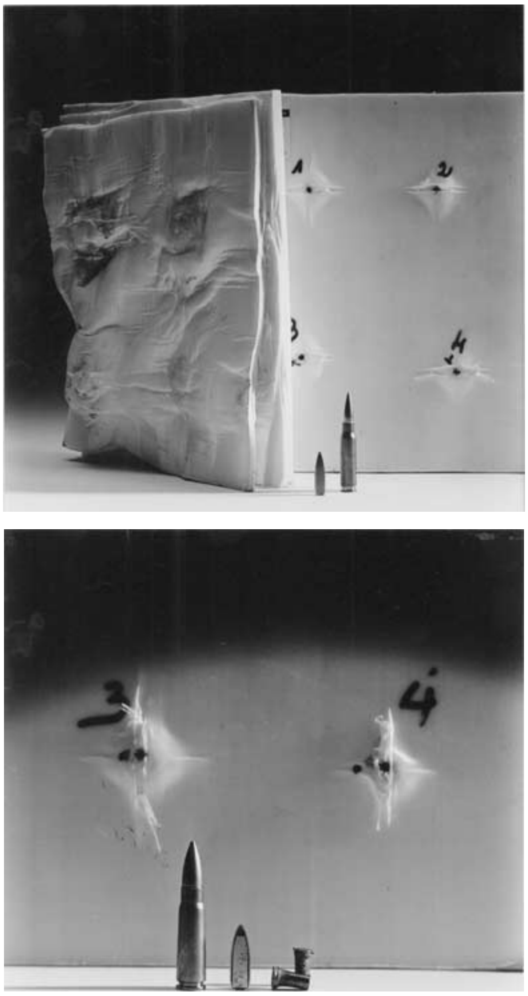


Figure 14 Panel tested against 7.62 × 38 Mild Steel Kalashnikov AK47.

that it will always be larger than the area of the first touch. The deformed area S_2 is sometimes more easy to see but in case of for instance the Nato Ball it should be estimated as the bullet is completely destroyed on stopping. The deformation energy of the bullets E_{absB} was first estimated by fitting a large number of test data. Comparing this with a few simple tests at low velocity showed that at least the order of magnitude was the same.

Very striking, we think, is the role of the bullet deformation in this model. This deformation absorbs a substantial part (often around 25%) of the bullet's total kinetic energy. On the picture below a 9 mm Para bullet is shown that has been stopped, see Fig. 13. Visible is the well known "mushroom" form of the deformed bullet, but it shows also the tunnel created by the penetrating non-deformed projectile. It looks as if the assumption in the model that the bullet deforms instantaneously is correct if this is not taken as "happening in a split second" but as "happening within one or two layers of the ballistic package".

Fig. 14 shows two photos of a panel that took 4 shots of the 7.62 Mild Steel Core Kalashnikov AK47. The first half of the panel is hardly deformed, the place where the deformation of the bullet starts is also the most deformed part of the panel. On the second photo the deformation of the mild steel core of this bullet is visible.

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