A Model for Ballistic Impact on Soft Armour

H. Billon

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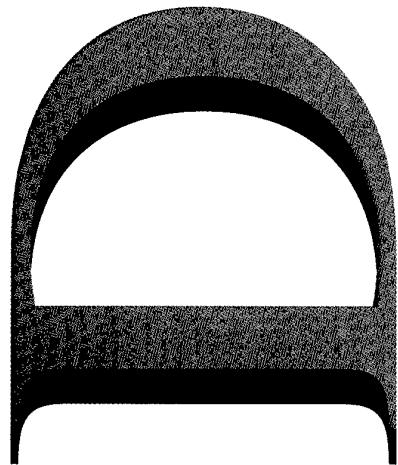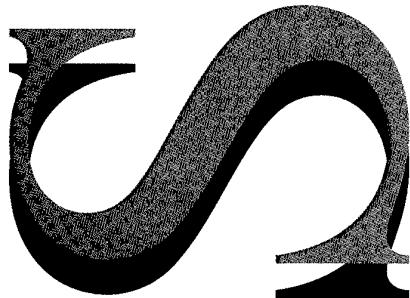
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H. Billon

Combatant Protection and Nutrition Branch
Aeronautical and Maritime Research Laboratory

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ABSTRACT

A model has been developed at AMRL to describe the impact penetration of soft armour. This model uses a direct - step method to determine the motion of the impacting projectile and of the fabric undergoing impact. The determination of the ballistic limit, residual velocity and the dependence of the ballistic limit on the areal density of the impacted fabric are discussed. Comparisons with experimental results are presented.

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Executive Summary

Armour constructed from ballistic fabrics (soft armour) is currently used by the Australian Defence Force (ADF) and other armed forces to protect personnel against injury from fragments and from low-velocity handgun ammunition. The development of models to describe the behaviour of different types of soft armour is desirable because such models would assist in the testing of novel armour design concepts and they would also permit a more rapid assessment of armour materials and designs that are proposed for procurement. A successful model can reduce the man-hour and material costs that are required for the evaluation of new types of armour.

A model describing the impact penetration of soft armour has been developed at AMRL. The model uses a direct - step analysis method to determine the motion of the impacting projectile and of the fabric undergoing impact. The model can be used to determine the ballistic limit and the residual velocity for soft armour. The model uses material property data for the fabric and the constituent yarns as inputs.

Comparisons of numerical results from the model with the experimental results of other authors and with the results of experiments conducted at AMRL indicate that output from the model is in good agreement with empirical data. The model accurately indicates the effect of changing the projectile kinetic energy and impact area as well as the effect on the impact process of changing the boundary of the impacted sample.

Authors

H. Billon
Combatant Protection and Nutrition Branch

Horace Billon graduated from the Royal Melbourne Institute of Technology with a B.Sc. in Applied Physics. He also has a Graduate Diploma in Mathematical Methods from the Royal Melbourne Institute of Technology. After working in the RAAF Quality Assurance Laboratories at Highett he joined AMRL in 1986. He works in the Combatant Protection and Nutrition Branch and his primary areas of interest are explosives rheology, electrostatics and ballistic protection.

Contents

1. Introduction

Armour constructed from fabric (soft armour) is currently in use by the Australian Defence Force and is also widely used by armed forces around the world as a means of providing protection against the impact of fragments and low-velocity handgun ammunition. There is interest in the development of mathematical models to describe the behaviour of the different types of fabric armour since these models make it easier to trial new armour design concepts. An additional benefit would be a more rapid assessment of armour materials and designs that are proposed for procurement. The resultant cost savings in man-hours and materials required for testing is obvious.

Roylance [1] has developed a ballistic impact model for soft armour based on the assumption that the fabric may be simulated by a pin-jointed network. Roylance used the method of direct-step analysis to solve the equations of motion that describe the impact process. A similar mathematical method was employed by Shim et al. [2] who also assumed that the impacted fabric could be replaced by an appropriate pin-jointed network.

A model, similar in concept to the above models, has been developed at AMRL. It is the purpose of this paper to describe some features of the model and to then use the model to analyse some ballistic impact phenomena in order to assess the accuracy and reliability of the model through comparison with experimental results. In this work the ballistic limit (the threshold impact velocity value for target penetration by a projectile) and the residual velocity curve are predicted for a variety of fabrics and these results are then compared with empirical data. In addition, the variation of ballistic limit with areal density of the fabric is predicted and is then compared with ballistic impact data for multiple fabric layers. The mechanism by which the ballistic limit varies with the kinetic energy and with the shape and size of the impacting projectile is determined and the character of the solution is also determined as a function of the mesh size of the pin-jointed network.

2. Experimental

2.1 Apparatus

The ballistic limit for fabrics was experimentally determined by means of a gas gun that had been previously designed and built by AMRL [3]. The gun uses compressed nitrogen or helium to propel either 5.59 mm diameter (1.1 g) or 7.62 mm diameter (2.82 g) fragment simulating projectiles (FSPs) at velocities in the range of 200 m/s to 750 m/s. Through the use of sabots, the firing of a wide range of sub-calibre projectiles is also possible.

2.2 Materials

Kevlar® KM2 fabric was obtained from DuPont (Australia) and the properties of the material are listed in Table 1 and Table 2 together with data from reference [1].

Table 1: Material Property Parameters for Ballistic Fabrics

Fabric	Areal Density (kg/m²)	Weave	Ends/cm	Picks/cm	Tex (Warp)	Tex (Weft)
Kevlar® KM2[1]	0.248	Plain	12	12	96	94
Kevlar® 29 [1]	0.4218	Orthogonal	16	16	130	130

(1) These values were determined at AMRL

Table 2: Material Property Parameters for Fabric Yarns

Fabric	Modulus (g/denier)	Breaking Strain
Kevlar® KM2 [4]	570	0.04
Kevlar® 29 [1]	550	0.04

2.3 Experimental Method

The ballistic limit was determined by firing shots into the target at a range of velocities and in increments of 20 m/s. The firing velocities were increased or decreased until the ballistic limit of the target was bracketed by two firing velocities. This is considered to occur when there is a difference of 10 m/s or less between a penetrating and a non-penetrating shot.

3. The Model

3.1 Description

The model uses the direct - step analysis method [5] to analyse the mechanics of the ballistic impact process. The panel is assumed to have the configuration of a collection of pin-jointed segments. The panel is square in shape and because of the symmetry of the problem it is only necessary to consider one half of a single quadrant of the square. This fact considerably reduces software memory requirements. The mass of the segments is adjusted to match the areal density (the mass per unit area) of the panel. The projectile impact is assumed to be restricted to the central crossover of the panel. The source code for the model has been written in both BASIC (for a personal computer) and FORTRAN (numerically - intensive mainframe computer). Two languages were used for the source code because the numerically-intensive computer operates on a batch submission, time-sharing system and it was more convenient to run smaller prototype versions of the software interactively on the PC rather than to use the more cumbersome batch submission process for these initial investigations. This model is similar in concept to the one described by Roylance [1].

The model begins an analysis by setting initial and boundary conditions for the segment crossovers. All crossovers are initially at rest except for the central crossover whose initial velocity is made equal to the velocity of the impacting projectile. The model describes the motion of the segment crossovers which have three degrees of freedom. The only constraint to the motion of any crossover is provided by the forces exerted on the crossover by the segments linking it to neighbouring crossovers. The motion of the crossovers is determined by these forces which result from the displacement of the crossovers from their original positions which creates strains in the segments linking the crossovers.

The implementation of any numerical scheme requires consideration of the aspects of numerical stability and accuracy. In the present work this is accomplished by using the von Neumann condition [6]

$$\delta l \le c \delta t \qquad (1)$$

where δl is the mesh spacing, δt is the time step and c is the longitudinal wave speed of the yarn in the woven fabric. In practice the inequality is replaced with an equals sign and it was found that accurate results were obtained when c was set equal to the sonic velocity of the unwoven yarn divided by the square root of two [1].

The sonic velocity of the unwoven yarn was divided by the square root of two because the effective mass per unit length of the segments that represent the layer of fabric is increased by a factor of two. This increased mass per unit length occurs because the

mass of a repeating unit that constitutes a strand of the fabric layer is equivalent to the mass of two segments.

3.2 Material Property Data

The model accepts as input numerical values of the material properties of the fabric and its constituent yarns. The model incorporates the constitutive equation (expressing the relation between the stress and strain for the yarn) and the yarn failure criterion into the software in the form of subroutines. The use of subroutines increases the versatility of the software since it makes it easy for updated values of the material parameters, resulting from increased knowledge, to be readily incorporated into the model as these become available.

For this same reason the mathematical equations used by the model to represent the constitutive equation and the failure criterion can easily be varied to reflect any changes in impact properties that might be encountered during the assessment of different types of fabrics.

In this paper all results have been obtained using an elastic constitutive equation of the form:

$$\sigma = E\varepsilon \qquad (2)$$

where σ is the stress, E is Young's modulus and ε is the strain. All these quantities are measured along a segment within the fabric layer.

An ultimate strain failure criterion has been used for the yarn segments. This is of the form:

$$\varepsilon \geq \varepsilon_f \qquad (3)$$

where ε_f is the ultimate strain value. Alternatives to the above consitutive equation and failure criterion are available in the literature for some materials [2].

The difference between the operation of this model and various semi-empirical curve-fitting approaches must be stressed. While the semi-empirical 'models' require the input of results from at least a small number of impact experiments, the model described in this paper does not require the input of any impact data to obtain results. This model uses material property data for the fabric yarn to predict the ballistic impact properties of the woven fabric without the necessity for conducting any preliminary impact experiments.

4. Results and Discussion

4.1 The Effect of the Mesh Spacing on Numerical Results

In an effort to determine the optimum mesh spacing for the model, numerical results were obtained for different mesh sizes. These results are presented in Table 3.

Table 3: The Variation of Ballistic Limit with Mesh Size. Kevlar® 29. Single Layer. Areal Density: 0.4 kg/m². Impact with a 5.59 mm Diameter FSP. FSP Mass, $m_P = 1.1 \times 10^{-3}$ kg. 0.203 m × 0.203 m Square Sample.

Mesh Spacing	Ballistic Limit	Kinetic Energy	Projectile Area	Kinetic Energy Per Unit Area
δL	v_B	$\frac{1}{2}m_P v_B^2$	A	$\frac{\left(m_B v_B^2\right)}{(2A)}$
(m)	(m/s)	(m/s)	(m²)	(J/m²)
2.03×10^{-2}	350	73	3.24×10^{-4}	2.3×10^5
1.02×10^{-2}	300	51	8.09×10^{-5}	6.3×10^5
5.59×10^{-3}	190	20	2.45×10^{-5}	8.2×10^5
2.54×10^{-3}	60	2	5.06×10^{-6}	4.0×10^5
1.02×10^{-3}	15	0.1	8.09×10^{-7}	1.2×10^5

The projectile area A in Table 3 was calculated under the assumption that the projectile was a cylinder with an end - face diameter equivalent to the mesh spacing δL, therefore:

$$A = \pi \left(\delta L \big/ 2\right)^2 \qquad (4)$$

From Table 3 it is obvious that although the kinetic energy varies significantly, the kinetic energy/unit area is approximately constant when the projectile cross-sectional area is calculated as though it possessed a diameter equivalent to the mesh spacing. This fact is consistent with the assumption, used in developing the model, that impact occurs over an area that is of equivalent value to the area of a segment crossover. The experimental value for the ballistic limit for the Kevlar® panel in Table 3 is 200 m/s and it is notable that this value is similar to the value of 190 m/s that is obtained for the ballistic limit when a mesh spacing of 5.59 mm (equal to the projectile diameter) is

used. From Table 3 it is evident that when other mesh sizes were used there was significant deviation from the experimental value of the ballistic limit.

An inference that can be drawn from these results is that the mesh spacing necessary to simulate a particular impact situation is not arbitrary but must be chosen to reflect the shape and size of the projectile. If a particular situation required the use of an arbitrary mesh size then it would be necessary to modify the model in order to more accurately reflect the shape and size of the impacting projectile.

An example serves to illustrate this point. Much ballistic testing is currently conducted using a 25.4 mm diameter circular boundary to delimit the area of the test sample. If it was necessary to simulate an impact event for such a small region with a standard 1.1 g FSP then it would be necessary to use the present model with a very coarse mesh. This is because the 1.1 g projectile has a diameter of 5.59 mm which only divides approximately 5 times into 25.4 mm, leading to the requirement for a 5 x 5 mesh. If a fine mesh was required for increased accuracy, then the present model would need to be modified so that the 5.59 mm diameter of the projectile could, at any point in time during the impact process, make contact with more than one crossover from the mesh.

4.2 A Comparison with Experimental Data.

Roylance [1] has compared residual velocity data with output from his model. Roylance's data for the ballistic impact of a single layer of Kevlar® 29 by a 0.22 calibre, 1.1 g FSP was digitised and compared with the results of the AMRL model. Using the model together with the material parameters presented in [1] a ballistic limit of 190 m/s was determined. It may be seen that this compares favorably with the experimental data which indicates a ballistic limit of approximately 200 m/s. It is also evident that there is good agreement when the residual velocities are compared. The AMRL code was run with an 18 x 18 mesh. The model also predicts that, at the same areal density, Nylon has a lower ballistic limit than Kevlar® 29, as expected from experimental results. In this case the model was run with a simple elastic constitutive equation and a maximum strain failure criterion.

Impact Penetration of Kevlar 29. One Layer. Areal Density 0.4 kg/m²
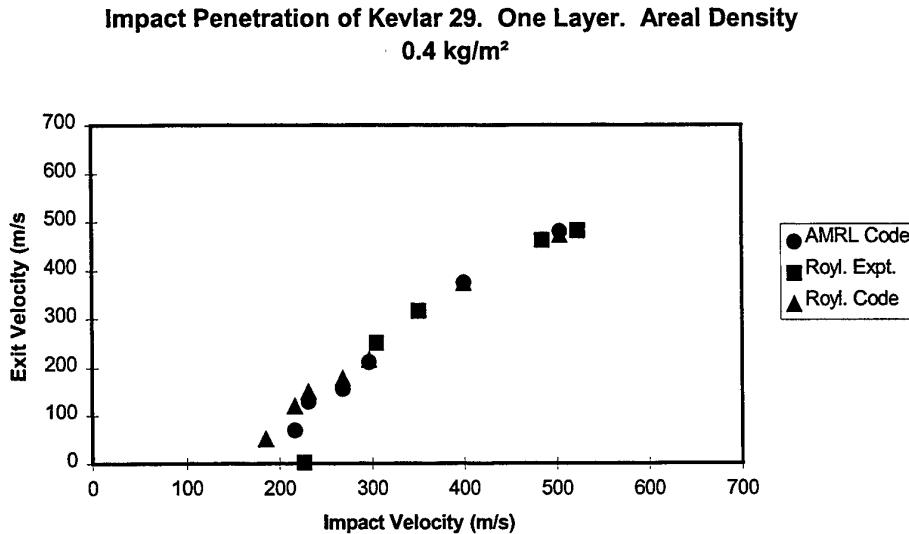
Figure 1: A Comparison of AMRL Numerical Results with Roylance's Data.

In the course of these numerical investigations it was found that the fabric property of crimp played an important role. The areal density of a fabric layer that is calculated using the assumption that the yarns are all straight is lower than the areal density value that is obtained from a direct measurement of the same fabric layer. The reason for this discrepancy is that the weaving process introduces crimp into the yarns. The results presented in Figure 1 were all calculated using the yarn crimp. When the model was used without including crimp for the results in Figure 1, it was found that the ballistic limit decreased from 190 m/s to 105 m/s. The importance of fabric crimp has been noted by other authors, for example Shim et al. [2]

A further comparison of the model output with experimental data was conducted by using the results of experiments at AMRL. These experiments were derived using the 5.59 mm FSP to assess the ballistic properties of a single layer of Kevlar® KM2 with an areal density of 0.248 kg/m². The sample was a square with dimensions of 0.203 m × 0.203 m.

Table 4: A Comparison between Experimental and Numerical Results for the Ballistic Impact of a Single Layer of Kevlar® KM2.

v_{impact}	v_{exit} (Experimental)	v_{exit} (Numerical)
(m/s)	(m/s)	(m/s)
187	73	129
191	119	136
198	151	144
202	132	149

Material property parameters were obtained from Table 1 and Table 2 and these were used by the model software. The numerically determined ballistic limit for this single layer was 150 m/s while the experimental ballistic limit was 185 m/s. Table 4 shows that there is also reasonable agreement between the numerical and experimental exit velocity values for impact velocities that are higher than the ballistic limit velocity. There is, therefore, good agreement between numerical predictions and values that are derived from experiment.

The observed exit velocity decreased from 151 m/s to 132 m/s when the impact velocity was increased from 198 m/s to 202 m/s. This counter - intuitive observation indicates that significant dispersion exists in measured values of the exit velocity. This experimental error will influence the comparison between numerical and experimental results.

The plot of exit velocity against impact velocity depicted in Figure 1 indicates that, at high values of the impact velocity, the curve may be approximately described by an equation of the form:

$$v_{exit} = v_{impact} \qquad (5)$$

A similar phenomenon has been observed during studies of the penetration of composite laminates subjected to high velocity impact. An explanation for this phenomenon has been advanced using the hypothesis that the dynamic penetration energy is constant for a range of impact velocities [7]. This hypothesis leads to the equation:

$$v_{exit} = \sqrt{v_{impact}^2 - \frac{2}{m_p} E_{DP}} \qquad (6)$$

Here m_p is the projectile mass and E_{DP} is the dynamic penetration energy for the impact process. It is easily seen from this equation that, for large impact velocities, the exit velocity tends towards equality with the impact velocity and that Equation (6) can then be approximated by Equation (5).

4.3 The Effect of Projectile Diameter, Mass, and Kinetic Energy on Ballistic Performance.

It has been stated [8] that an important parameter in optimizing the performance of an impacting projectile for the defeat of armour is the ratio:

$$R = m_p v_{impact}^2 / d^2 \qquad (7)$$

this ratio is proportional to the kinetic energy of the projectile divided by its cross sectional area. Here m_p is the projectile mass, v_{impact} the velocity at impact and d is the projectile diameter. The results in Table 5 were determined by using a mesh spacing equivalent in value to the projectile diameter. It was assumed that the projectile could be approximated by a cylinder.

Table 5: The Variation of Ballistic Performance with Projectile Mass and Diameter as Predicted by the Model. Kevlar® 29. Single Layer. Areal Density: 0.4 kg/m². 0.203 m × 0.203 m Square Sample.

Projectile Type (Projectile Diameter)	Projectile Mass (kg)	Projectile Area (m²)	Ballistic Limit (m/s)	Kinetic Energy (J)	Kinetic Energy/ Unit Area (J/m²)
FSP (5.56 mm)	1.1×10^{-3}	2.43×10^{-5}	190	19.86	8.2×10^5
FSP (7.62 mm)	2.82×10^{-3}	4.56×10^{-5}	160	36.10	7.9×10^5
FSP (12.7 mm)	4.147×10^{-3}	1.27×10^{-4}	175	63.50	5.0×10^5
Pistol Round (9 mm)	8.2×10^{-3}	6.36×10^{-5}	100	41.00	6.4×10^5

Table 5 indicates that the kinetic energy per unit area is approximately constant. This result agrees with Equation (7) and also implies that, with an appropriate mesh size, the model is capable of accounting, in part, for the shape and size of the projectile.

4.4 The Effect of the Boundary of the Impacted Panel on the Ballistic Limit

The effect that the boundary of the impacted test panel has on the ballistic limit is of crucial importance in the development of procedures for the testing of ballistic fabrics. Experimental work indicates that the ballistic limit of a fabric test sample decreases with decreasing sample size. It is important that the model is capable of predicting this phenomenon.

Table 6: The Variation of Predicted Ballistic Limit with Sample Size. Kevlar® 29. Single Layer. Areal Density: 0.4 kg/m². 1.1 g FSP.

Sample Dimensions (m²)	Ballistic Limit (m/s)
0.203 × 0.203	190
0.1015 × 0.1015	160

Table 6 indicates that the ballistic limit decreases as the dimensions of the fabric sample are reduced. This result is in agreement with experimental data.

4.5 Multiple Layers and The Effect of Fabric Areal Density on Ballistic Performance

It is possible to use the model to assess the ballistic impact of multiple layers of fabric. This has been accomplished by treating the layers of fabric as if there was no interaction between them. This is equivalent to an assumption of infinite spacing between the layers and numerical results are obtained by using the exit velocity from one layer as the impact velocity of the next layer. Numerical results were obtained for the impact of a 1.1 g FSP with an assembly consisting of a number of layers of Kevlar® KM2 where each layer in the assembly possessed an areal density of 0.248 kg/m². The boundary used for the numerical results was a square region of dimensions 10.16 cm × 10.16 cm. Experimental data had previously been obtained at AMRL for the variation of ballistic limit with areal density for fabric with a 2.54 cm diameter circular boundary. These results are presented in Figure 2.
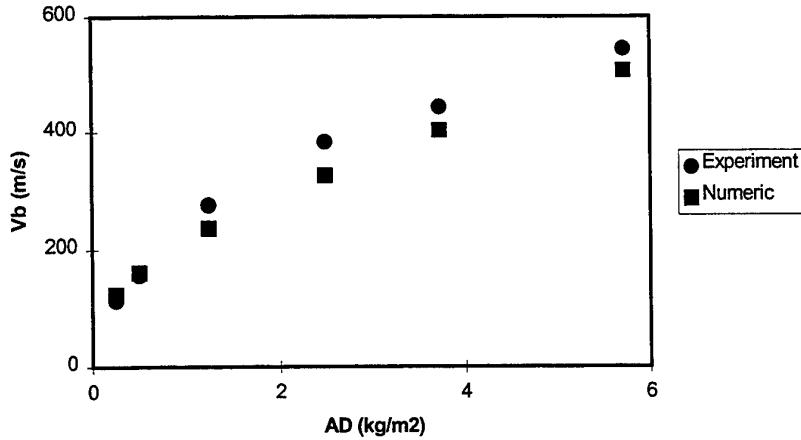
Figure 2: *Ballistic Limit as a Function of Areal Density. Kevlar® KM2. Experimental Results Obtained for a 2.54 cm Diameter Hole. Numerical Results Obtained for a 10.16 cm × 10.16 cm Square.*

Although the numerical and experimental results in Figure 2 were obtained using different boundary shapes and sizes and are therefore not directly comparable, there is only a small percentage error when the experimental and numerical results are compared. In addition, both sets of results have the same trend and indicate that the ballistic limit increases with the areal density and that the rate of increase of ballistic limit with areal density will decrease at higher areal densities. Because the present model requires the assumption of infinite spacing between the layers for the determination of the ballistic limit of a multi-layer system, it cannot be used for the study of system effects that might arise in multi-layer systems [9].

5. Conclusions

(1) A model that describes the ballistic impact of a fragment - simulating projectile with fabric armour has been developed.

(2) The model predicts the residual velocity curve and the ballistic limit for ballistic impact of a single layer of fabric.

(3) The model accurately indicates the effect of changing the projectile kinetic energy and impact area as well as the effect on the impact process of changing the size of the panel boundary.

6. Recommendations

(1) A model that is capable of more accurately describing the effects of inter-yarn friction and projectile shape as well as the effects of weave geometry should be developed.

(2) A model should be developed to more accurately determine the effects of multiple layers of fabric on the ballistic penetration process.

(3) The distribution of the experimentally observed exit velocities for a given impact velocity should be determined. This will permit a better assessment of the comparison between numerical and experimental results. Knowledge of the velocity distribution will also improve the effectiveness of the current experimental method when it is used for comparing different types of body armour.

7. Acknowledgements

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Horace Billon

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19. ABSTRACT

A model has been developed at AMRL to describe the impact penetration of soft armour. This model uses a direct - step method to determine the motion of the impacting projectile and of the fabric undergoing impact. The determination of the ballistic limit, residual velocity and the dependence of the ballistic limit on the areal density of the impacted fabric are discussed. Comparisons with experimental results are presented.