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# INFLUENCE OF FIBRE PROPERTIES ON BALLISTIC PENETRATION OF TEXTILE PANELS

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## SUMMARY

*A number of computer simulations have been performed in order to assess the ballistic penetration resistance of a series of textile panels. The results indicate that the rate of energy absorption of the panel increases monotonically with the fibre modulus, but that very high modulus material tends to exhibit poor impact resistance due to its low breaking strain. Aramid fibre seems to exhibit the best combination of high modulus while still maintaining reasonably high breaking strain. A 'master-curve' description of impact response has been developed from the computer results, which may be useful in minimising the number of full computer simulations necessary in the design of impact protective devices.*

## INTRODUCTION

Textile structures have been used to provide protection against ballistic threats since World War II, with the development then of flak jackets for aircraft crewmen. Now used widely by military and police personnel, these devices have been constructed principally of ballistic nylon or impregnated fibreglass. In recent years, however, improved devices have been developed using aramid fibres (DuPont's Kevlar® 29 or 49), and these are being considered for such additional applications as aircraft engine rotor-blade burst containment. Development and design of these devices has been largely empirical, and considerable effort has been expended to develop rational analytical tools which may be used in design, or at least in improving the designer's intuition.

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Although closed-form mathematical analyses can be applied to the initial ballistic response of a single fibre,[1] late-time effects arise due to stress wave interactions and reflections which make such closed-form analyses intractable. In the case of woven panels, each fibre crossover acts to reflect a portion of the stress wave which is propagating outward from the impact point, so here closed-form treatments are completely inapplicable. Accordingly, the present authors have attacked the impact problem with numerical analyses, and these computational treatments have proven to be of great value in understanding the ballistic event. These codes do not involve the idealising approximations needed in many other treatments, such as modelling the woven panel as a membrane, so that the user is able to proceed directly from fibre material properties, weave geometry, projectile velocity, etc.

## NUMERICAL ANALYSIS OF TEXTILE FABRIC IMPACT

The computer method used in the numerical analysis of textile impact is an outgrowth of a technique pioneered by Davids *et al.*[2] and applied successfully by them to a variety of wave propagation problems. This approach, which is similar in final form to finite-difference analysis, was first used by Lynch[3] to analyse the transverse impact of single fibres and later extended by Roylance *et al.* to the study of viscoelastic fibre impact[4] and impact of woven textile panels.[5] Referring to Fig. 1,

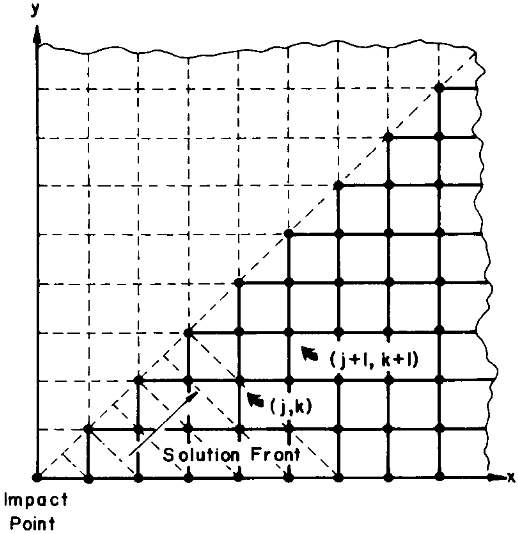

Fig. 1. Schematic of numerical approach used in analysis of fabric impact. Due to symmetry, one octant of the panel is idealised as shown. The computations begin at the point of impact and work outwards sweeping over the mesh repeatedly at various increments of time.

the woven panel is first idealised as an assemblage of pin-jointed, flexible fibre elements, each having a mass which makes the areal density of the idealised mesh equal to that of the panel being simulated. The initial projectile velocity is imposed on the node at the impact point, which causes a strain to develop in the adjacent elements. The tension resulting from this strain is computed from the material constitutive law, and this tension is used to calculate an acceleration in the neighbouring elements. The computer proceeds outwards from the impact point in this manner, using a momentum–impulse balance, a strain–displacement condition, and a constitutive equation to compute for each element the current values of tension, strain, velocity, position, and such ancillary but important quantities as strain energy and kinetic energy.

At the end of these calculations, a new projectile velocity is computed from the tensions acting on the projectile from the fibres, and the process is repeated for a new increment of time. In the development of such codes, due attention must be given to matters of efficiency, stability, and accuracy. As now developed, the fabric code produces data in excellent agreement with experiments, and does so at reasonable cost (approximately $15 for a typical impact event simulation, using MIT's IBM 370/168 system).

The numerical algorithm is finally terminated by simulated rupture of the fibres. Since the strain and tension histories are computed for each element in the mesh, a variety of failure criteria may be incorporated easily. The proper simulation of rupture is limited not by the ability to cast various fracture models in numerical form, but by the difficulty of obtaining reliable experimental data for the various fibre types applicable to these high rates. A similar difficulty arises in the formulation of the constitutive equations, in which material properties are used to relate strain to stress. A variety of linear and nonlinear viscoelastic models have been formulated and demonstrated successfully in the impact code,[6] but serious difficulties arise in obtaining suitable numerical values for the various coefficients in these models. However, it is hoped that the availability of a code which can model the mechanics of the impact process will provide an incentive for experimental research aimed at obtaining the numerical properties needed for a more detailed analysis.

## PARAMETRIC MATERIALS STUDY

The influence of fibre properties on penetration resistance has been studied by means of a number of computer simulations of zero-obliquity ballistic impact on various textile panels. These results help validate the reliability of the model in that it can be shown to generate data in agreement with experimental observations. It also provides a means of illustrating certain phenomena, such as transient wave propagation, which are not generally observable experimentally; in this regard one's intuitive understanding of the impact even is improved considerably.

Numerical results have been obtained for a series of four simulated orthogonally woven, 203 mm square panels, impacted at zero obliquity by a 0·22 calibre projectile weighing 1·10 g. Such a projectile is commonly used in experimental work to simulate the effect of fragment impact. The edges of the panels were assumed to be clamped, although penetration generally occurred before the arrival of stress waves at the clamps; the nature of the edge boundary conditions is therefore relatively unimportant. Rather than perform straightforward parametric tests in which one variable, such as fibre modulus, is varied while others are held constant, it was decided to simulate a series of actual fabrics for which input data was available either from the weaver or from laboratory measurement. The computer results can thus be compared directly with laboratory ballistic tests, although in general more than one variable is changed in each simulation. In particular, the fabric panel weight varies slightly for each material type, although the effect of this was expected to be small relative to the large change resulting from the markedly different fibre moduli.

For the purpose of these parametric tests, only very simple constitutive and fracture models were employed. Although more realistic models are available as described earlier, the numerical data necessary for input into these models are generally not available. For this reason the fibre stiffness was set to a constant value obtained from handbook quasistatic stress–strain data, and the failure criterion was a simple maximum-breaking-strain check, where the maximum allowed was also taken from quasistatic test results.

The data for the four fabric types are shown in Table 1.

TABLE 1

GEOMETRIC AND MATERIALS PROPERTIES USED IN FABRIC STUDIES

| *Fibre* | *Nylon* | *Kevlar 29$^{TM}$* | *Kevlar 49$^{TM}$* | *Graphite* |
|---|---|---|---|---|
| Tensile modulus, GPa | 7·77 | 70·4 | 127 | 430 |
| Fracture strain, % | 14·0 | 4·0 | 2·2 | 1·1 |
| Fabric mass, g | 19·53 | 17·38 | 25·75 | 27·09 |
| Yarn denier | 1050 | 1167 | 1485 | 1500 |
| Yarns/cm | 17 | 16 | 16 | 16 |

Figure 2 shows typical predictions of strain wave profiles obtained at various times after a 400 m/s impact on the various fabrics. Unlike impact on a single elastic fibre, in which a constant level of strain is propagated outwards from the impact point, the array of fibre crossover junctions around the impact point in a fabric serves to reflect a portion of the outward-propagating wave back toward the impact point. As a result, the strain is always greatest at the point of impact, and grows continuously with time (unless the projectile is slowed appreciably by the panel). Both the level of strain and the rate of propagation are governed by the fibre modulus and density. Graphite fibres have the highest modulus of the four materials, and thus propagate the lowest level of strain at the highest rate. As the modulus is decreased, the strain level is increased and the wavespeed is decreased.

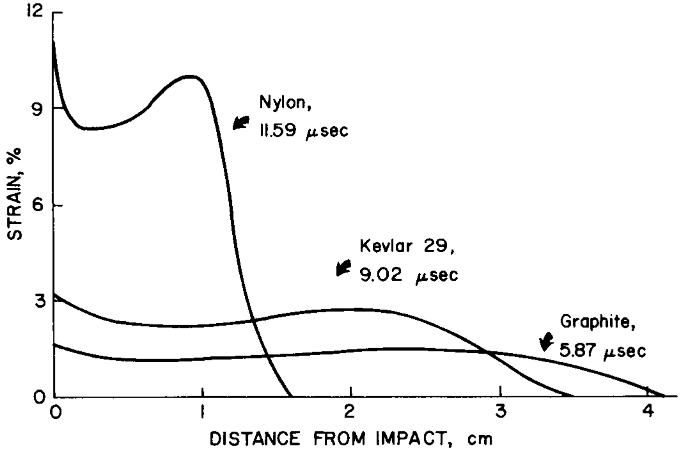

Fig. 2. Strain profiles along orthogonal yarns passing through the impact point, at various times after a 400 m/s impact on various fabric panels.

Penetration dynamics can also be illustrated by the missile deceleration as shown in Fig. 3, where reductions of missile velocity by various fabric materials are given. Note that the ability of the various fabrics to decelerate the projectile increases monotonically with the fibre modulus.

The energy extracted from the projectile is partitioned into strain and kinetic energy in the panel. This energy partition is easily computed, and Fig. 4 indicates that approximately half the total fabric energy absorption is stored in the form of strain energy. The kinetic energy associated with transverse velocity is approximately double that associated with in-plane velocity components. Energy absorption is a convenient indicator of panel ballistic performance, and Fig. 5 illustrates the relative energy absorption capabilities of the four pañel materials

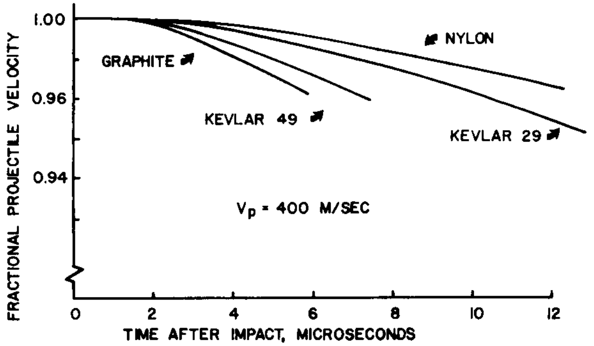

Fig. 3. Normalised projectile deceleration after zero-obliquity impact on the various panels.

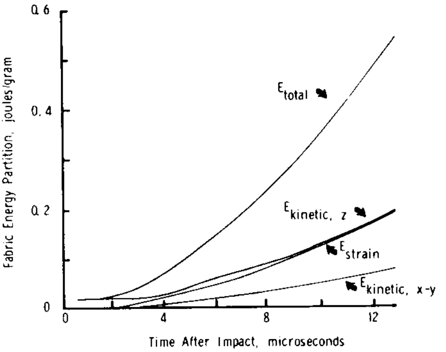

Fig. 4. Fabric energy absorption after a 400 m/s impact on a Kevlar 29 panel. The $z$ subscript indicates motion in the direction of projectile travel, while $x$ and $y$ are in the plane of the panel.

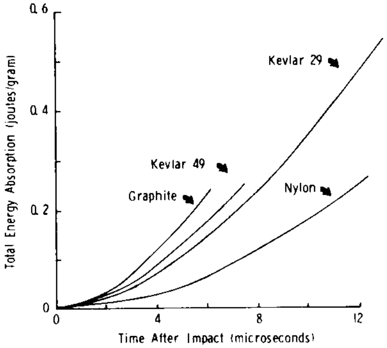

Fig. 5. Comparison of energy absorption in the various panels after a 400 m/s impact. Each curve is terminated on the right by rupture of the panel at the point of impact.

studied. It is seen that the high fibre modulus of the graphite panel leads to a rapid rate of energy absorption, but that fracture occurs before the panel has been able to extract as much of the projectile's impact energy as the lower-modulus fabrics. Conversely, nylon requires a long time-to-penetration, but the energy absorption rate is too low to lead to a large total energy absorption. The Kevlar 29 panel exhibits the best combination of energy absorption rate and long time-to-penetration and is thus predicted to be the superior ballistic material of the four types studies.

## AN APPROXIMATE ANALYSIS

It is natural to seek some simple relationship between fibre material properties and fabric ballistic resistance. The preceding results lead one to expect that the most important parameter governing the stress history in the fabric before fracture is the fibre modulus. The modulus controls wavespeed, and thus the distance the impact disturbance will have travelled in a given time. The modulus also controls the level of strain which will be generated by impact at a given velocity. The relation is not known explicitly for fabrics, but can be determined by performing computer experiments using the numerical code.

Figure 6 depicts the computed strain history at the point of impact for 400 m/s impacts upon the four model fabrics. It is clearly seen that an increase in fibre modulus decreases the strain for a given time, in correlation with the same result for single fibres. The fabric impact is considerably more complex than single-fibre impact, however; the point of impact feels not only the continuing influence of the projectile, but is also continually bombarded by wavelets reflected and diverted from adjacent fibre crossovers. The situation is too complex to permit simple

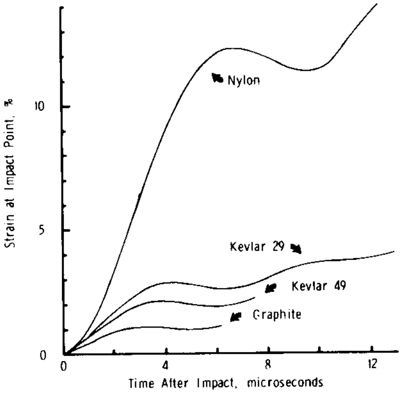

Fig. 6. Impact-point strain history in the various fabrics after zero-obliquity impact.

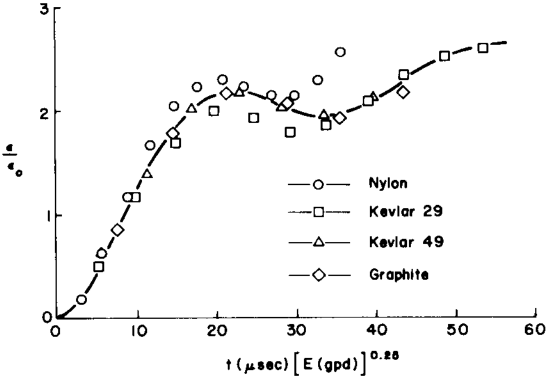

Fig. 7. 'Master curve' for impact-point strain history after zero-obliquity impact. $\varepsilon_0$ is the value predicted by rate-independent theory for the strain generated in a single fibre by a transverse impact at the same velocity,[1] and $E$ is the fibre modulus in grams per denier. (1 gpd = 1 MPa/88·3 $\rho$, $\rho$ = density, gm/cm$^3$.)

generalisations, but the nonlinear form of the strain histories for the various fabrics can be taken to reflect the influence of wave interactions occurring in a region whose size increases quadratically with time. Note also that the shape of the strain histories varies consistently with fibre modulus: the time for arrival of the first peak, for instance, decreases monotonically with modulus.

If one normalises the magnitude of the ordinal values in Fig. 6 by the value of strain which would be developed in a single fibre by transverse impact at the same projectile velocity,[1] the strain magnitudes of the four curves achieve comparable values. This procedure essentially compensates the curves for the effect of the fibre modulus on the impact-induced strain. The shift of the curves along the abscissa, however, is less clear. The rate at which the strain increases at the impact point is governed by the complex interactions of waves travelling about within the constantly expanding region of influence, and is beyond simple visualisation. On average, the time necessary for a wave to reflect and return eventually to the impact point should decrease inversely with the wavespeed, i.e. inversely with root of the modulus. However, the size of the region in which stress waves are travelling at any given time also depends on the wavespeed, and one would expect that a larger region of influence would decrease the rate at which reflected and diverted wavelets are able to return to the impact point.

It is found that the time after impact at which the first peak in the strain occurs varies linearly, with good correlation, with the fourth root of the fibre modulus (or the square root of the wavespeed). Using this observation, which is likely related to the geometry of the region of influence, one can compensate the abscissal values of

Fig. 6 by the factor $E^{0.25}$. The result of the ordinal and abscissal normalisation is shown in Fig. 7, where a curve valid for all four fabrics is developed.

This 'master curve' provides a means of performing preliminary armour design. Since the normalising factors are known once the dynamic modulus of the fibre is specified, one can generate a strain versus time curve from Fig. 7 applicable to a particular fabric and impact velocity. The time for rupture is the time at which the impact-induced strain exceeds the fibre's dynamic breaking strain. As in the fibre case, we then see that ballistic resistance is a balance between high fibre modulus leading to high wavespeeds and lower strains, and fibre breaking strain.

This approach is approximate in several respects, however, and is thus limited to preliminary design. First, it is seen in Fig. 7 that perfect correlation among all four test fabrics is not attained, the nylon showing a deviation at high strain. Similar deviations in other fabrics might be observed as well. Secondly, the curve of Fig. 7 was generated from computer experiments at relatively high velocity, so that projectile slowdown was not an appreciable factor. At low impact velocities, the fabric is able to decelerate the projectile and even bring it to rest. The effect of projectile slowdown is to generate unloading waves in the fabric which travel simultaneously with those previously described. This unloading would have a strong influence on the curves such as the one in Fig. 7, causing the curves to pass through a maximum and decrease thereafter in those cases in which the fabric is able to defeat the projectile. For these cases, complete treatment using the numerical code would be necessary.

## ACKNOWLEDGEMENT

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