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TEXTILE BALLISTIC PERFORMANCE

(DATA BASE)

Final Technical Report

by

Professor J.W.S.Hearle
Dr.C.M.Leech
Dr.C.R.Cork

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University of Manchester, Institute of Science and Technology
P.O. Box 88,
Sackville Street,
Manchester M60 1QD,
England.

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Nylon and Kevlar textiles are examined for their performance against impact by a 1gm projectile, when subject to impact velocities up to 200 m/s. The textiles are of varying areal density, and of varying layer composition and their performance is examined theoretically and experimentally. The theoretical models have been previously developed and are the characteristic model, membrane finite element and a multilayer finite element; the experimental /Cont'd.

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facility had also been previously established and this report is aimed at correlating the experimental and theoretical facilities and to establish a data base of results.

It was quickly found that the theoretical models favoured nylon over Kevlar for ballistic performance, whereas experimentally Kevlar is superior. It is also shown that the deformation process is correctly modelled and this then suggests that the fracture criterion must be reconsidered; possible fracture mechanisms to be included in textile failure criterion are stated for future consideration.

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ABSTRACT

Nylon and Kevlar textiles are examined for their performance against impact by a 1gm projectile, when subject to impact velocities up to 2000 m/s. The textiles are of varying areal density, and of varying layer composition and their performance is examined theoretically and experimentally. The theoretical models have been previously developed and are the characteristic model, membrane finite element and a multilayer finite element; the experimental facility had also been previously established and this report is aimed at correlating the experimental and theoretical facilities and to establish a data base of results.

It was quickly found that the theoretical models favoured nylon over Kevlar for ballistic performance, whereas experimentally Kevlar is superior. It is also shown that the deformation process is correctly modelled and this then suggests that the fracture criterion must be reconsidered; possible fracture mechanisms to be included in textile failure criterion are stated for future consideration.

Key words.

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INTRODUCTION

This report uses previously established computational
(ref,1,2,3,4) and experimental (ref.5) facilities at UMIST
to generate a data bank for the behaviour of synthetic fibre
textiles against ballistic impact.

The basic computational procedures used are firstly the
method of characteristics which uses the propagational
aspects in yarns to model the propagation of signals in yarn
structure, namely textiles and secondly the finite element
method which segments the plane of the textile into small
elements and uses the principle of least action and the
energy quantities to develope equations of motion for the
element corners. This method is more appropriate for the
detail of yarn crimp and for examining viscoelastic effects.
The finite element method generates two codes, firstly the
named membrane model which properly accounts for crimp and
the multilayer-model which accounts for stacked textiles
forming a layered structure.

The data basic was established using the following variable
parameters.

i)   ballistic parameters (impact velocity, projectile
        mass).
ii)   Component parameters (yarn stress strain behaviour)
iii)   panel configuration (area density)
iv)   structure parameters (layer composition)

The experimental facilities previously developed consist of
a cartridge gun used to launch a 1gm projectile, .22"
cylindrical projectile. The impact velocity, and if
penetration occurs, the exit velocity of the projectile can
be measured, it is therefore possible to calculate the V_{50}
or the energy absorption. In addition a multiflash
photographic system has been developed in order to study the
projectile deceleration dynamics and the configuration of
the fabric during impact.

THE COMPUTATIONAL INVESTIGATION

The computer experiments were conducted on a bank of launch
and textile data, for Kevlar and nylon; this data is
summarised in Tables 1a, 1b and the three computer models
drew on this data to yield fabric behaviour with time. From
this the projectile kinematics (kinetic energy, velocity)
and fabric deformation (indentation, strain, strain energy)
are extracted and ultimately used to deduce the fabric
survival or integribility and ballistic resistance. The
results are presented in a following section.

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BALLISTIC RESISTANCE OF SYNTHETIC CLOTH

Kevlar   breaking strain=0.032
          projectile mass=1gm.

Case No.	Model	Area den. gm./s.sq.	Impact vel m/s	Imp. energy joules		Exit vel. m/s	Res. energy joules	Contact time microsec.	Max. strain	% Energy abs.	% Energy left
1	characteristics	400	500	125		496	123.01	5	.032	1.59	98.41
2	characteristics	400	1000	500		998	498.00	2	.032	.40	99.60
3	membrane	400	1000	500		999	499.00	1.2	.032	.20	99.80
4	multi(3)-layer	400	1000	500		991	491.04	4	.032	1.79	98.21
5	characteristics	400	1500	1125		1498	1122.00	1.4	.032	.27	99.73
6	characteristics	400	2000	2000		1999	1998.00	1	.032	.10	99.90
7	membrane	400	2000	2000		1999	1998.00	.5	.032	.10	99.90
8	multi(3)-layer	400	2000	2000		1999	1998.00	2	.032	.10	99.90
9	characteristics	100	500	125		499	124.50	4	.032	.40	99.60
10	characteristics	500	500	125		496	123.01	4	.032	1.59	98.41
11	characteristics	1000	500	125		450	101.25	10	.032	19.00	81.00
12	membrane	1000	500	125		385	74.11	18	.032	40.71	59.29
13	multi(3)-layer	1000	500	125		483	116.64	10	.032	6.68	93.72
14	characteristics	1500	500	125		275	37.81	26	.032	69.75	30.25
15	characteristics	2000	500	125		0	.00	130	.029	100.00	.00
16	membrane	2000	500	125		0	.00	66	.024	100.00	.00
17	multi(3)-layer	2000	500	125		487	118.58	10	.032	5.13	94.87
18	membrane	3000	500	125		0	.00	65	.022	100.00	.00
19	multi(3)-layer	3000	500	125		497	123.50	9	.032	1.20	98.20
20	membrane	4000	500	125		0	.00	63	.021	100.00	.00
21	multi(3)-layer	4000	500	125		497	123.50	9	.032	1.20	98.80
22	membrane	1158	150	11.25		0	.00	108	.011	100.00	.00

Table 1a

BALLISTIC RESISTANCE OF SYNTHETIC CLOTH

Nylon-a
breaking strain=0.24
projectile mass=1gm.

Case No.	Model	Area den. gm./m.sq.	Impact vel. m/s	Imp. energy joules	Exit vel. m/s	Res. energy joules	Contact time microsec.	Max. strain	% Energy abs.	% Energy left
1	characteristics	400	100	5	0	.00	245	.146	100.00	.00
2	characteristics	400	300	45	260	33.80	35	.24	24.89	75.11
3	characteristics	400	400	80	379	71.82	n.a.	.24	10.22	89.78
4	characteristics	400	500	125	485	117.61	16	.24	5.91	94.09
5	characteristics	400	1000	500	994	494.02	7	.24	1.20	98.80
6	membrane	400	1000	500	998	498.00	3	.24	.40	99.60
7	multi (3)-layer	400	1000	500	152	11.55	2.5	.24	97.69	2.31
8	characteristics	400	2000	2000	1997	1994.00	3.8	.24	.30	99.70
9	membrane	400	2000	2000	1999	1998.00	1.5	.24	.10	99.90
10	multi (3)-layer	400	2000	2000	220	24.20	6	.24	98.79	1.21
11	characteristics	100	500	125	497	123.50	14	.24	1.20	98.80
12	characteristics	200	500	125	492	121.03	n.a.	.24	3.17	96.83
13	characteristics	500	500	125	480	115.20	16	.24	7.84	92.16
14	characteristics	600	500	125	464	107.65	n.a.	.24	13.88	86.12
15	characteristics	800	500	125	433	93.74	n.a.	.24	25.00	75.00
16	characteristics	1000	500	125	350	61.25	40	.24	51.00	49.00
17	membrane	1000	500	125	390	76.05	24	.24	39.16	60.84
18	multi (3)-layer	1000	500	125	153	11.70	57	.24	90.64	9.36
19	characteristics	1100	500	125	0	.00	n.a.	n.a.	100.00	.00
20	characteristics	1500	500	125	0	.00	130	.19	100.00	.00
21	characteristics	2000	500	125	0	.00	135	.17	100.00	.00
22	membrane	2000	500	125	0	.00	175	.196	100.00	.00
23	multi (3)-layer	2000	500	125	487	118.58	25	.24	5.13	94.87
24	membrane	3000	500	125	0	.00	134	.187	100.00	.00
25	multi (3)-layer	3000	500	125	490	120.05	25	.24	3.96	96.04
26	membrane	4000	500	125	0	.00	86	.184	100.00	.00
27	multi (3)-layer	4000	500	125	491	120.54	14	.24	3.57	96.43
28	characteristics	100	150	11.25	0	.00	n.a.	n.a.	100.00	.00
29	characteristics	100	300	45	292	42.63	n.a.	.24	5.26	94.74
30	characteristics	200	100	5	0	.00	n.a.	n.a.	100.00	.00
31	characteristics	800	400	80	0	.00	n.a.	n.a.	100.00	.00
32	characteristics	1158	1500	1125	1462	1068.72	n.a.	.24	5.00	95.00
33	characteristics	1158	150	11.25	0	.00	263	.067	100.00	.00
34	characteristics	1560	700	245	0	.00	n.a.	.24	100.00	.00
35	characteristics	1500	1000	500	949	450.30	n.a.	.24	9.94	90.06
36	characteristics	1500	1500	1125	1470	1080.45	n.a.	.24	3.96	96.04
37	characteristics	2000	1000	500	0	.00	n.a.	n.a.	100.00	.00

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Table 1b

THE EXPERIMENTAL INVESTIGATION

The experimental program was designed to obtain data on the V_{50} (the velocity at which 50% of projectiles are defeated) and the energy absorption of multilayer nylon and Kevlar fabrics. In order that the experimental work should be as directly comparable to the computer models the projectile was chosen to be a blunt nosed cylinder rather than the chisel nosed fragment simulator more generally used. In additon the fabric has a fixed boundary in the computational model and is likewise clamped in the experimental case.

Apart from the V_{50} and the energy absorbtion there are secondary output parameters concerned with the mechanism of the projectile fabric interaction . Examples of these parameters are

i) projectile decleration and the applied force;
ii) stress and strain distribution within the fabric;
iii) the position of the transverse wave;
iv) the time to failure.

It is of great interest to compare these outputs with observations of actual impact either to confirm computer prediction or in order to indicate where improvements in the simulation can be made.

There is currently a lack of published data on woven fabrics in this area. Notable exceptions are the independent work of Maheux[6], Roylance[7] and Morrison[8]. Roylance has observed photographically the transverse impact of a single layer of nylon fabric at velocities between 116 and 537 m/sec and provides data on the position of the transverse wave (cone radius) as a function of time for the lowest impact velocity.

Morrison has applied multi-flash silhouette photography to observed the response to impact of Kevlar fabrics incorporated in composite structures. These results have been compared to that of the fabric alone. Morrison uses data from single layer impact to determine the development of the pyramid deformation with time, and goes on to predict the partition of energy within the fabric during impact.

The aim of the present work was to extend this work to produce i) directly comparable results between Kevlar and nylon, and ii) information on the effect of the number of layers on the above mentioned parameters.

The above listed output parameters cannot all be measured either easily or directly. It was therefore decided that the current work should concentrate on the parameters which

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could be measured photographically.   These are :

i)   the position of the pyramid apex as a function of
        time;
ii)   the position of the transverse wave front, also a
        function of time;
iii)   the time to failure.

The first parameter approximates to the projectile position.
From these results the apex velocity and the transverse wave
velocity can be calculated.

For the purpose of the present experimental work, two
experimental variables were chosen, namely :

i)   the area density of the multi-layered fabric;
ii)   The fabric material.

In terms of end use the aim is always to optimise the latter
in order to minimise the former.

EXPERIMENTAL METHOD

Multi-layered samples were prepared such that the overall
fabric weight was as close as possible to 1000, 2000, 3000
and 4000 g m^{-2}.

One Kevlar (351 g m^{-2}) and one nylon (241 g m^{-2}) fabric were
tested. The nominal impact velocity was 500m s^{-1}.

The test method was as follows :-

An opaque screen was illuminated by a series of three light
flashes of short duration.   A still camera was located
facing the screen.   The camera was aimed along the plane of
the back surface of the fabric at right angles to the
direction of flight of the projectile.   The camera was
opened in a dark room and the lights were triggered by a
circuit breaker just before impact.   The actual times of
each flash were recorded as a trace of light intensity
against time on a transient recorder using a photodiode.
The actual times of the flashes were found to differ from
the times set on the delay box.   This was attributed to
delays inherent in the lights. The aim was to provide data
at 10 s internals and also at 20μs or 40μs interval if
penetration did not occur before the last flash.

EXPERIMENTAL RESULTS

Typical photographs obtained by the above method are shown in figures 6a, b. In figure 6a the silhouette of the pyramid of deformation is shown at approximately 10, 20, 30 and 40 μs after impact. Figure 6a (A to G) are nylon of nominal area density of 2000, 3000 and 4000 g m^{-2} respectively, whilst D,E,F,G shows corresponding photographs of Kevlar.

No results were obtained for nylon at 1000 g m^{-2} as penetration occurred too quickly after impact, and as will be explained below, at least two images are required in order to normalise results.

In figure 6b similar photographs of penetration are displayed; here, however, the deformations are shown up to the time of penetration, if this occurs.

All the multi-flash photographs are shown to the same scale. The minor divisions in the scale were of the order of millimeters, and the observed deformations were of the order of centimetres.

From these photographs and others the following were determined:

i)   the pyramid height above the surface of the last layer (h),

ii)   The distance between the left and right transverse wave front (D)

The time measured by the experiment was the time after the triggering of the electronic system by the projectile. Due to minor variations in impact velocity and also because of the change in the position of the last fabric layer due to variations in the sample thickness, results from different tests on different samples count not be immediately compared. In order to overcome this problem the measured times normalised such that the instant of first movement of the last layer was equal to t_0. This was accomplished by assuming an approximate constant velocity of apex, between the times of the first two light falshes (giving results h_1, t_1 and h_2, t_2). The normalised time t_n was for any time t was found by

$$t_n = t + K$$

where $K = t_1 - \dfrac{h_1(t_1 - t_2)}{(h_1 - h_2)}$

The results for nylon and Kevlar are shown as plots of pyramid height v time in figures 6 c, e respectively.

No measurable deceleration was seen for the nylon data so the data points were statistically fitted to a straight line.   It is not, however, assumed that no decelleration occurs, just that the decelleration is too small to be observable.   Indeed, table 2

Area Density ($g\ m^{-2}$)	Velocity ($m\ s^{-1}$)
1928	382
2892	341
4097	277

TABLE 2

shows the average velocity of the apex during the observable projectile-fabric interation.   This shows a reduction in mean interation velocity with increased area-density.

In contrast to the nylon data the Kevlar curves are concave downward reflecting an observable decelleration.

In both figures 6c,d,e,f, the cut off of the curve indicates that penetration occurs.   No cut-off is observed for the 3861 $g\ m^{-2}$ Kevlar as penetration did not occur.

Figures 6g, h are plots of the distance of the transverse wave from the centre of impact (D/2) against time.   There are no theoretical curve fits available but the plots are included for the sake of completeness.

This distance is measured along the warp direction such that the distance D corresponds to the pyramid diagonal.   As before the nylon data has been fitted to straight lines. The similarity between figures either 6c and 6h suggests a linear relation between the pyramid height and width of the base.   Figure 6i shows that this is indeed the case for both nylon and Kevlar.   The ratio between the base and height being greater for Kevlar.   There are also small differences in this relation dependent on the number of layers.

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CONCLUSION AND DISCUSSION OF COMPUTATIONAL RESULTS.

The numerical results predict that nylon is better than
Kevlar, which is in contradiction to experiments.

Three possible explanations surface

1.   The analysis and computation is in error
2.   The fabric properties are wrong
3.   The failure criteria is incorrect.

The first two explanations seem unlikely in view of the
agreement observed in Figures 6 c,d,e,f.   Significant
discrepancy is obvious not in the curve, but in the ending
of the curve, namely the break point which is delayed in the
computation model beyond the experimental results.   The
exception to this is the lower area density Kevlar textiles
(<1000 g/m^2), when the computation and experiments are in
quite good agreement.

The probable cause for the lack of agreement, is the
definition of failure criteria.   Kevlar fibres have been
assumed to break at 0.032 strain and nylon at 0.24 strain.
These are the quoted static fibre strain values and have
been incorporated as a textile failure criteria (including
the effect of crimp).   These criteria will have to be
re-evaluated in the light of the above, and it would appear
that other effects beside straight tension failure of fibres
are present when the textile fails.

They can be

a)   early fibre failure due to strain rate (Viscoelastic)
b)   premature failure in nylon due to local heating
c)   cutting
d)   bending, due to decrimping and flexure

for fibre failure and

e)   accentuated stretch due to structure bending
f)   yarn opening to allow projectile to proceed
g)   fibre finishes to inhibit load equalisation

      for the textile 'failure'.

Obviously these questions cannot be answered here but do
suggest the need for a more detailed study of the localised
phenomenon.   It is suggested here that since fibre rate
behaviours are known point (a) can be considered in an
iterative or empirical manner.   Also the correlation of
experimental and computation results can be used to give a

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measure of the fibre failure criteria when used in a
structure , at high strain rates and against localised
impact. This correlation and reverse criterion estimates
were shown in the Appendix.

In conclusion it follows that

a)   fibre tensile strength as obtained in a static test is
of little use as a criterion for these fibres when used in a
structure, at high rates of straining and in a localised
impact.

b)   the fibres need to be stiff and light (favouring
Kevlar) so that as much of the textile structure is
effective in the impact as possible (large cone area).

c)   the fibre should be rough to give forth good fibre to
fibre contact and thus sharing the impact over the structure
and secondly to resist the opening force which is presented
during impact especially by ogival or pointed projectiles.

d)   they should be of low tex so that their flexure in
crimp and in the impact process does not give rise to much
higher strains (from bending).

e)   consideration should be given to the effects of
thermodynamic energy and how temperature rise influences
stiffness.

f)   resistance to cutting and crushing by the projectile
must be considered again in the light of the above lack of
agreement in the terminal phase between experimental
observation and computer models based upon static tensile
fibre strength.

COMPUTATIONAL RESULTS

The three models used in predicting the performance of
ballistic textiles are as follows :

a)   The characteristics model uses the yarn material
properties (mass and stiffness) and the yarn direction to
determine the propagation of signals through the textile;
there is no crimp or thickness modelling and it expected
that for fast events this model would be quite accurate.

b)   the membrane model which, based upon finite element
theory can account in detail for the yarn path though the
textile (crimp); however the model since it uses finite
element theory cannot usefully predict high speed events
since stress wave propagation is not accurately accounted
for.

c) The multi-layer (finite element) model accounts for the layers (in this case, three) which are stacked together and can relatively slide and individually fail; because the structure thickness is now included this model should work well at lower speeds since at higher speeds the contacting layer can deform and indeed fail before the other layers have even started to move. This model would be used for thick structures with bending stiffness at lower velocities.

These models have been run for nylon and Kevlar for a series of impact velocities and fabric weights. The accompanying tables 1a and 1b summarise the fabric performance by considering exit velocity (and its derivative, residual energy, energy absorption) contact time (to break or stop) and the maximum strain encountered in the fibres.

The results of the computational models are presented in the following manner for both nylon A and Kevlar.

Firstly a carpet plot Fig.1a,b axes being impact velocity and area density; on these plots each case is entered, a point indicating that the projectile is stopped and a cross indicates that the fabric has failed. Also shown is the divide between stopping and penetration as estimated from a fit to existing experimental data.

Generally it is seen that the computer predictions give an upper value for the necessary impact velocities for a given textile structure (area density); it is also seen that more data is needed in the vicinity of the experimental data fit for the multilayer model since every prediction resulted in textile failure. This indeed may be the better model to use, although initially it was not thought to be as accurate as the characteristic or membrane models.

Without exception each prediction showed that nylon performed better than Kevlar from the point of stopping; however in comparable cases when both materials stopped the projectile Kevlar stopped it quicker (more deceleration). This is a consequence of the fact that Kevlar is stiffer and breaks at lower strain. Thus the energy absorbed may be less in the breaking cases, but in the stopping case the stiffness gives a faster arrest.

The divide between the break and stopping cases (crosses and dots) give a curve for the extraction of the V_{50} against area density.

The figures 1c,d show the extrapolation of V_{50} against area density using interpolation of the latter graphs.

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Fig. 1a

Nylon Proj. mass=1gm

Breaking map

Fig. 1b

Kevlar

Break Stopped
● ○   Characteristics
▲ △   Membrane
■ □   Multilayer
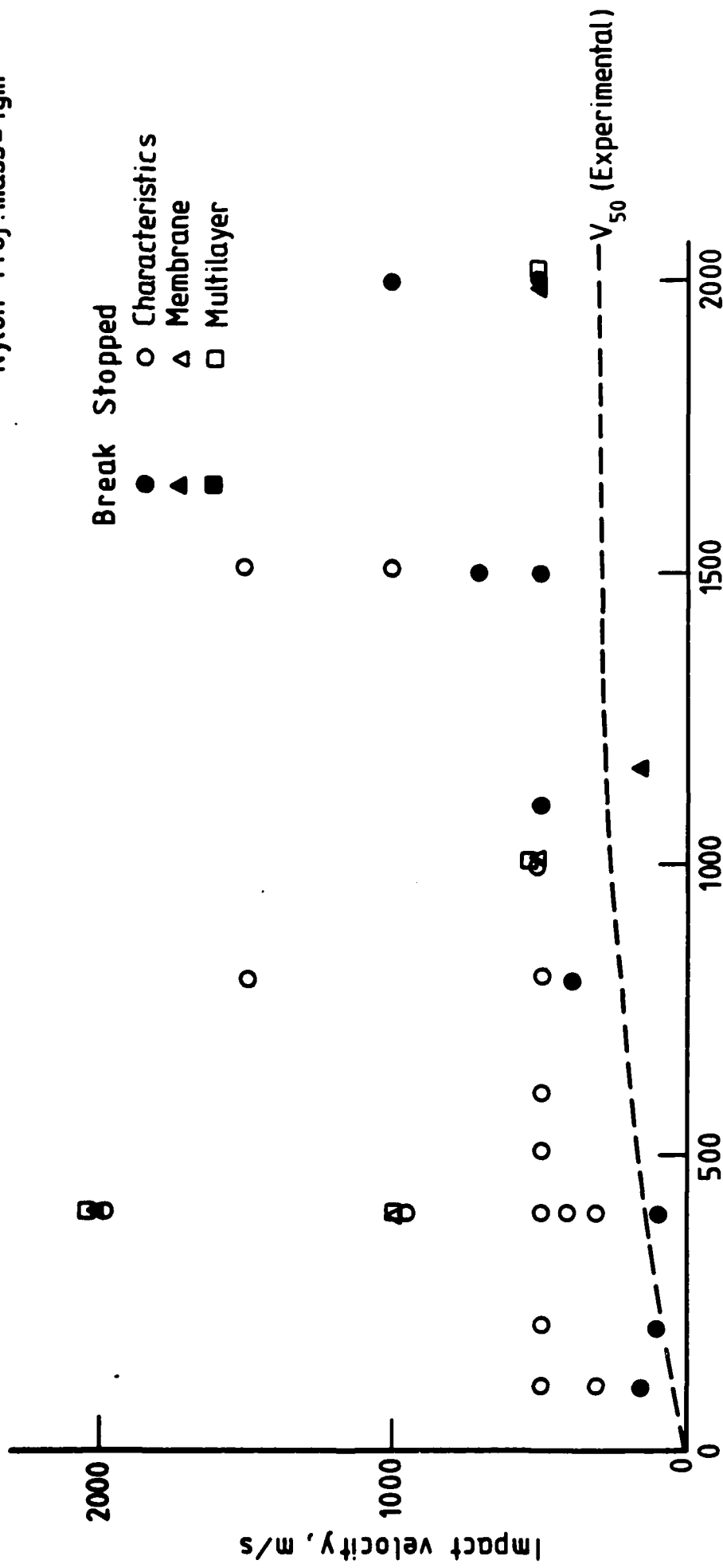
V_{50} (Experimental)
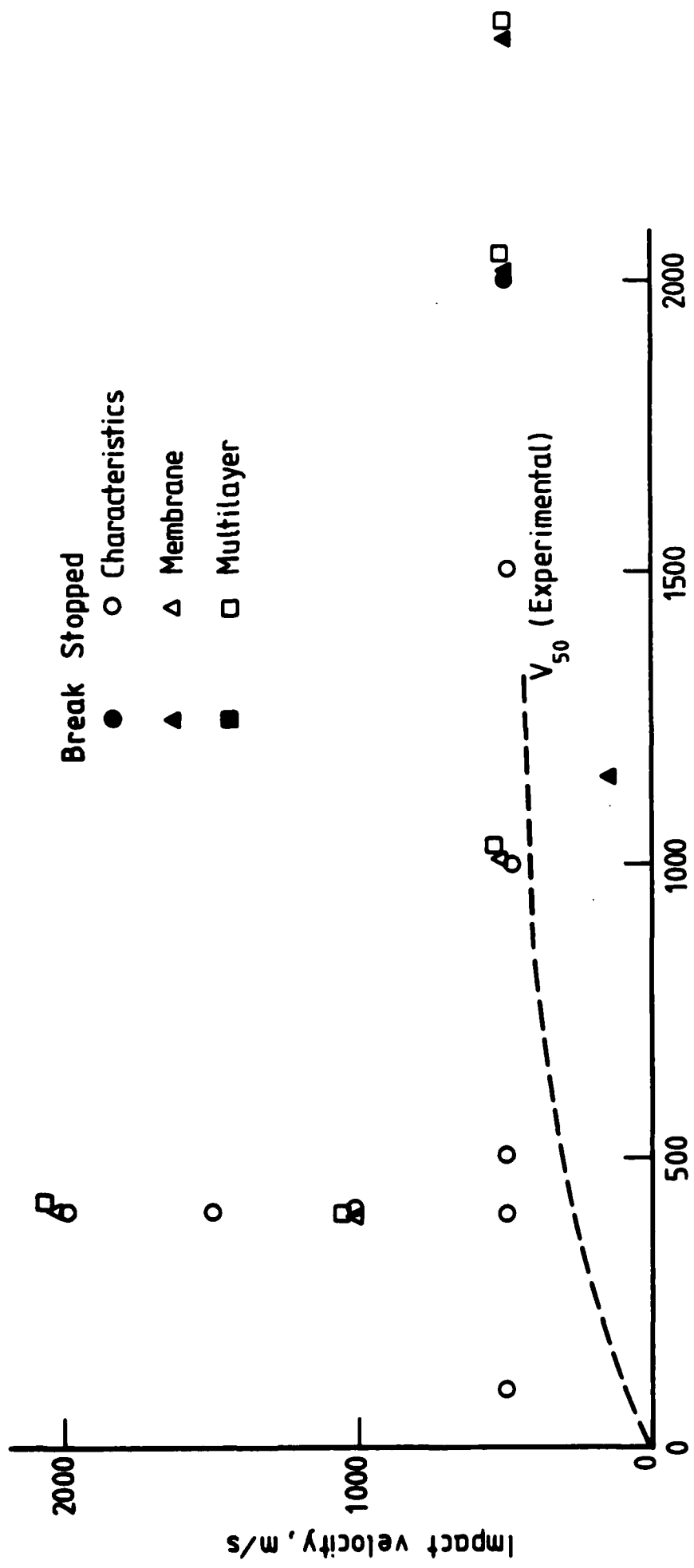
Area density, gm/m

Breaking map

Impact velocity, m/s

13

Fig. 1c

V_{50} v Fabric weight

Fabric weight, g/m^2

V_{50}, m/s

Nylon
$\varepsilon_{break} = 0.24$

V_{50} (Experimental)

14

Fig. 1d

Kevlar

- Break
- x Safe
- ■ Adeyefa, Fig. 5.34

V_{50} (Experimental)

Fabric weight, g/m^{-2}

V_{50} m/s
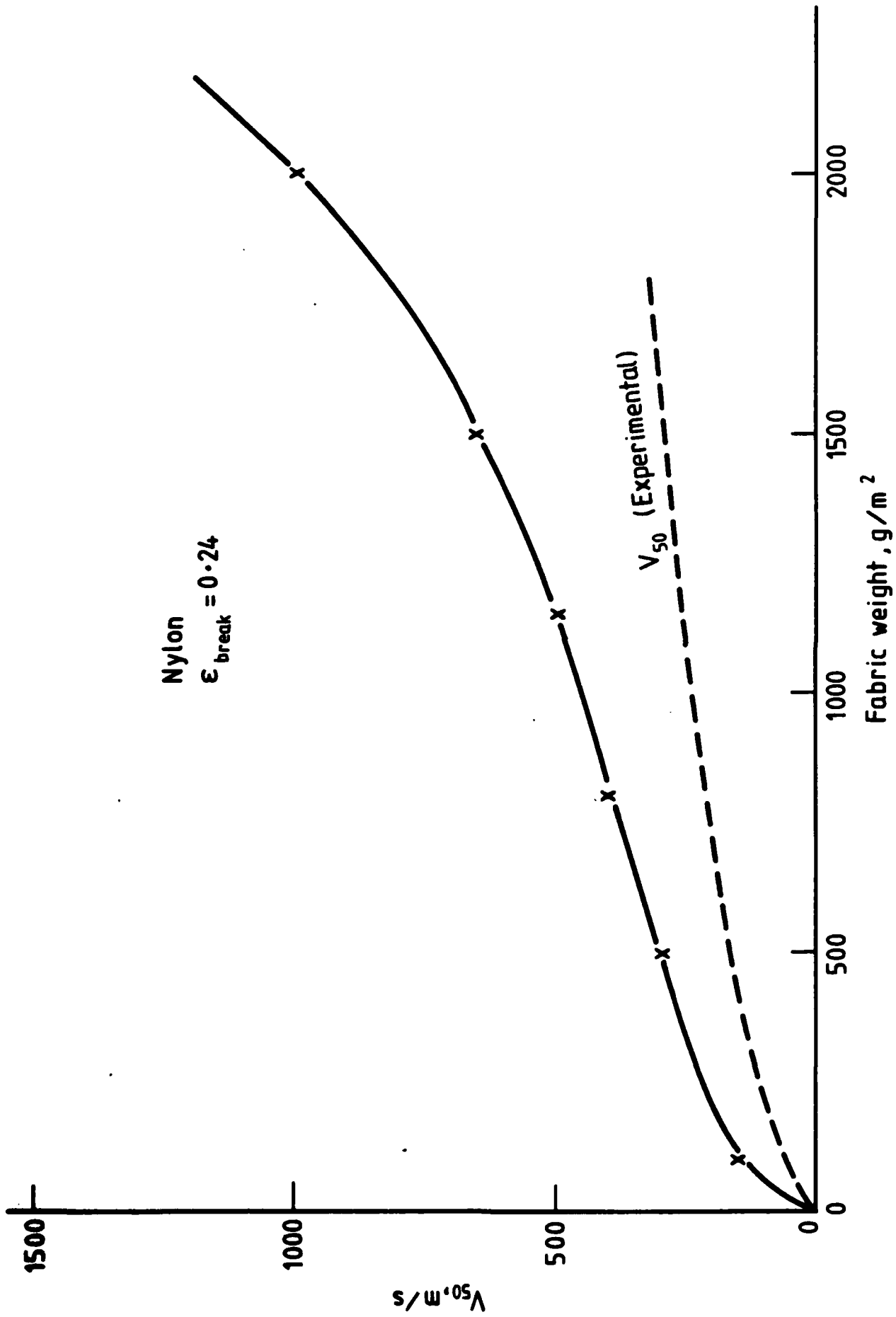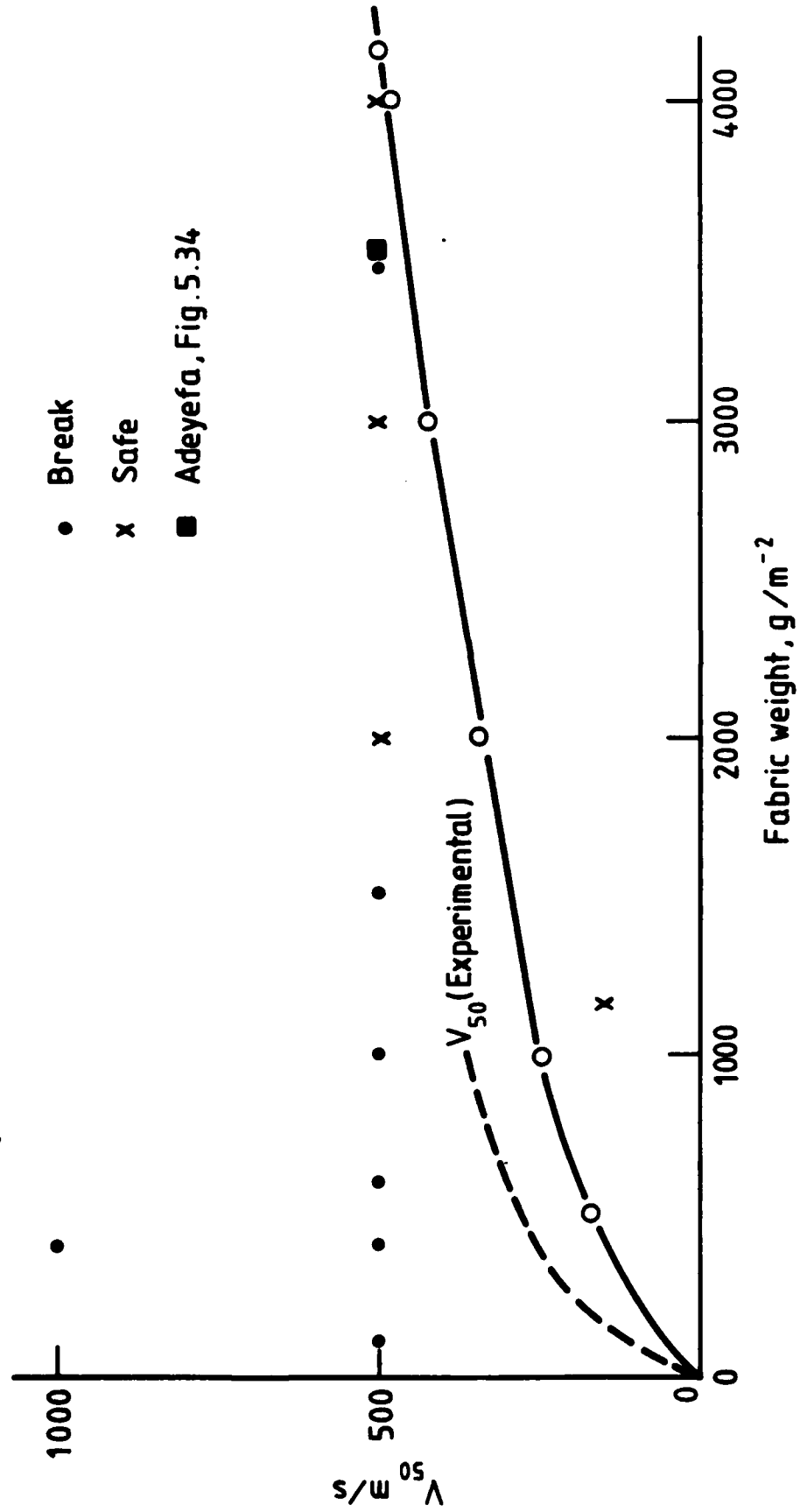
Figures 2a, to d show the energy absorbed plotted against
area density for different impact velocities; when the
projectile has stopped there is 100% energy absorption and
thus at those points the graph is parallel to the fabric
weight axis; the poor performance of Kevlar as predicted by
the multilayer model is shown in Fig.2d by those points
lying near the horizontal axis. These point do lie below
the experimental fit and more data at lower velocities are
now suggested. Fig.2c also shows the poor predicted
performance as indicated by the multilayer model, in this
case for nylon.

Fig. 2a

Energy v fabric weight

Fabric weight, g/m^{-2}

Energy v fabric weight

Kevlar

$\varepsilon_{break} = 0.032$

$-x- V_0 = 500 \text{m/s}$

$\dfrac{E_{ADS}}{E_{IMP}}$

Fig. 2b

Fig. 2c

% Energy absorbed vs Area density, gm/m²

Nylon — Impact speed = 500 m/s, Proj. mass = 1 gm

- Characteristic
- × Membrane
- ○ Multilayer (3 layers)

Experimental fit

Kevlar Impact speed 500m/s
Proj. mass 1gm

Fig.2d

20

x Characteristics
■ Membrane
● Multilayer
+ Experimental

% Energy absorbed

Area density (gm / m²)
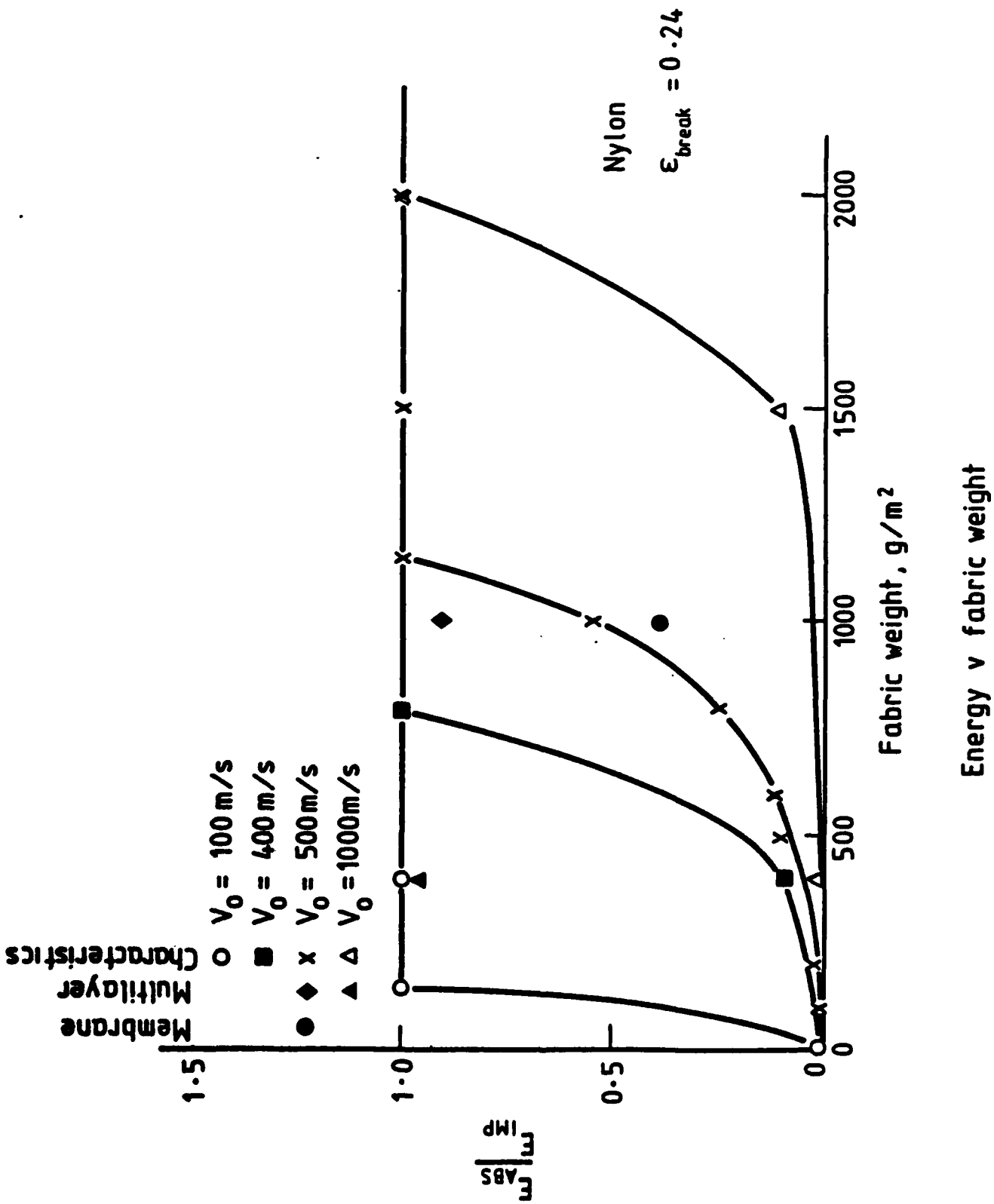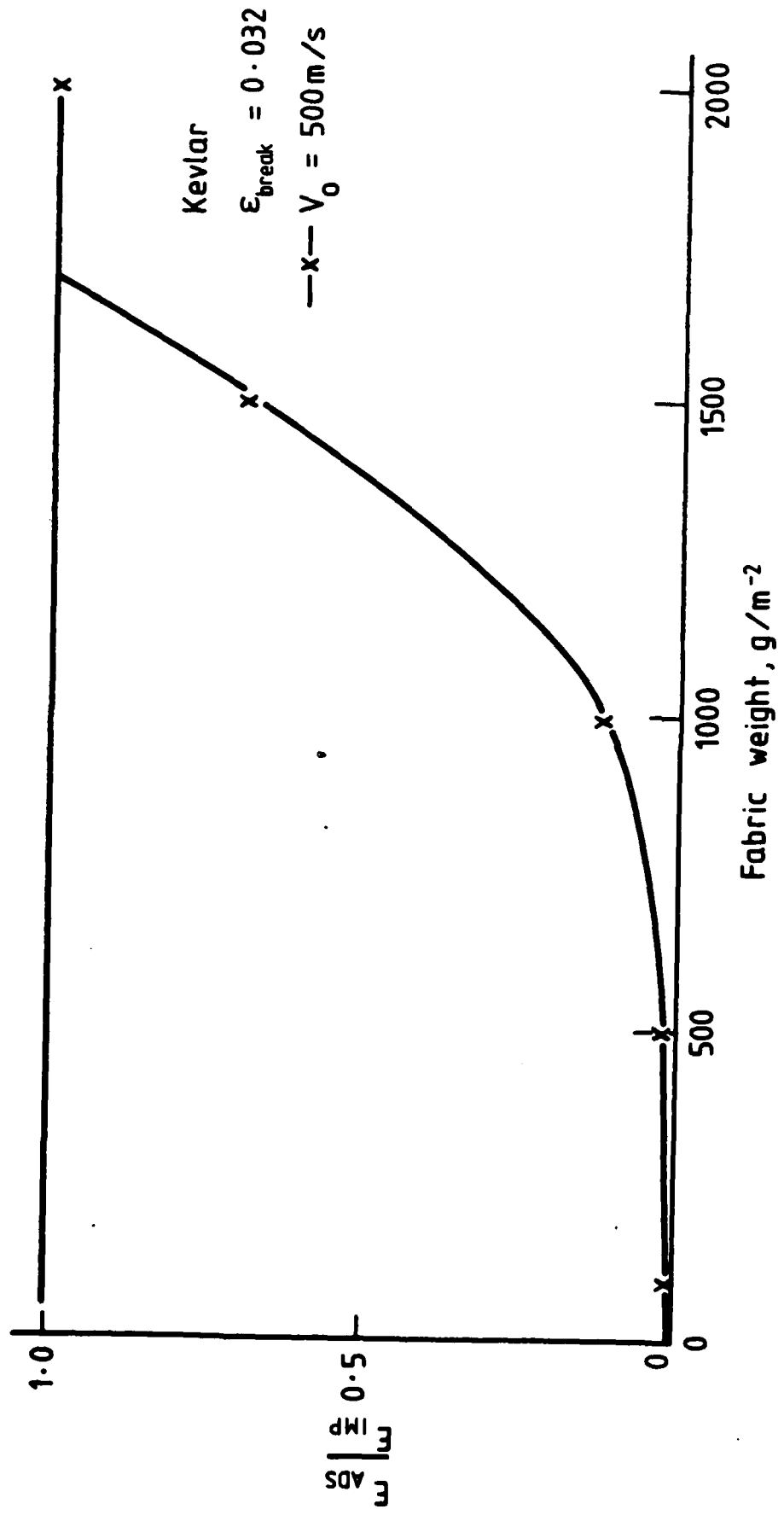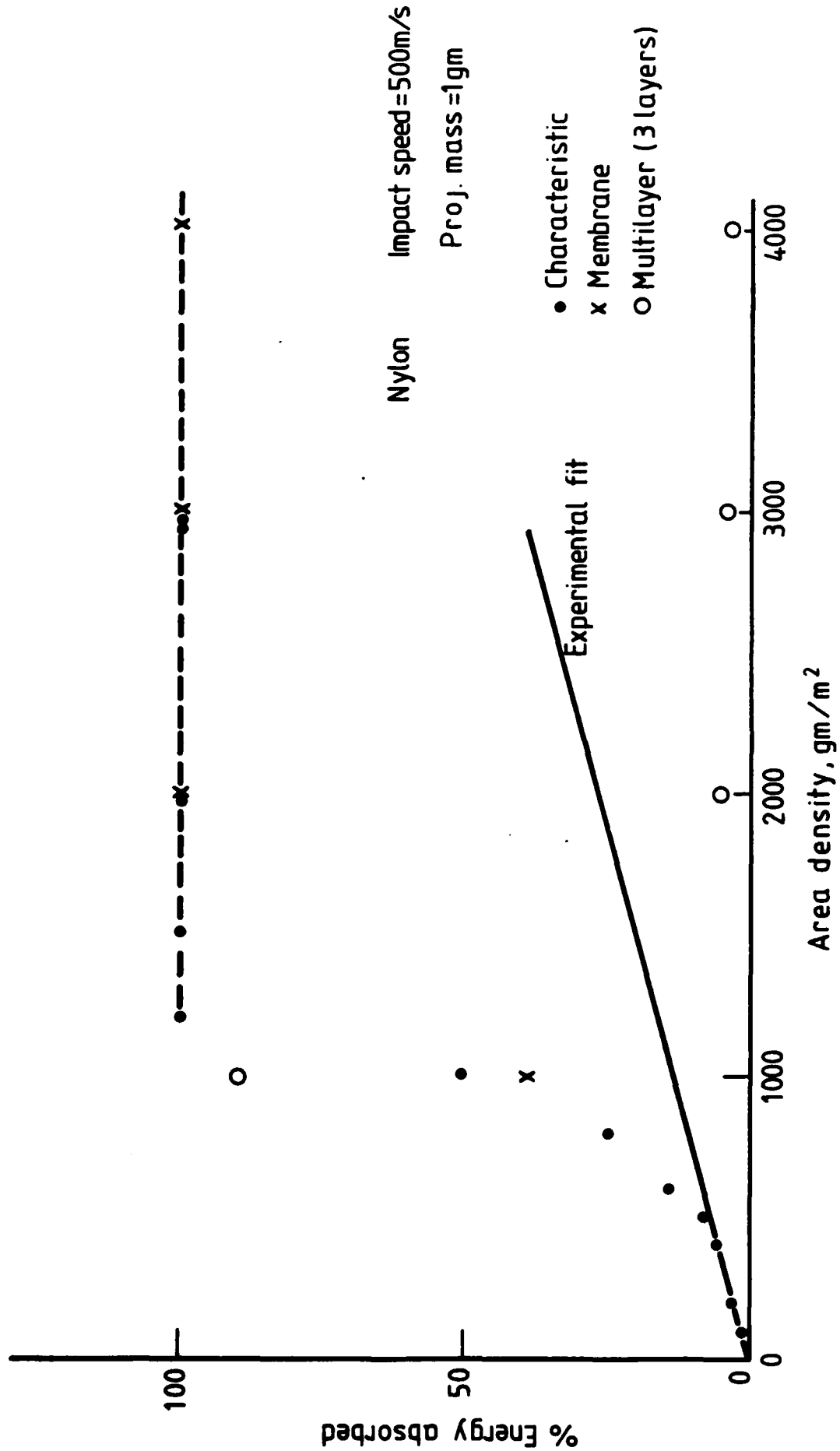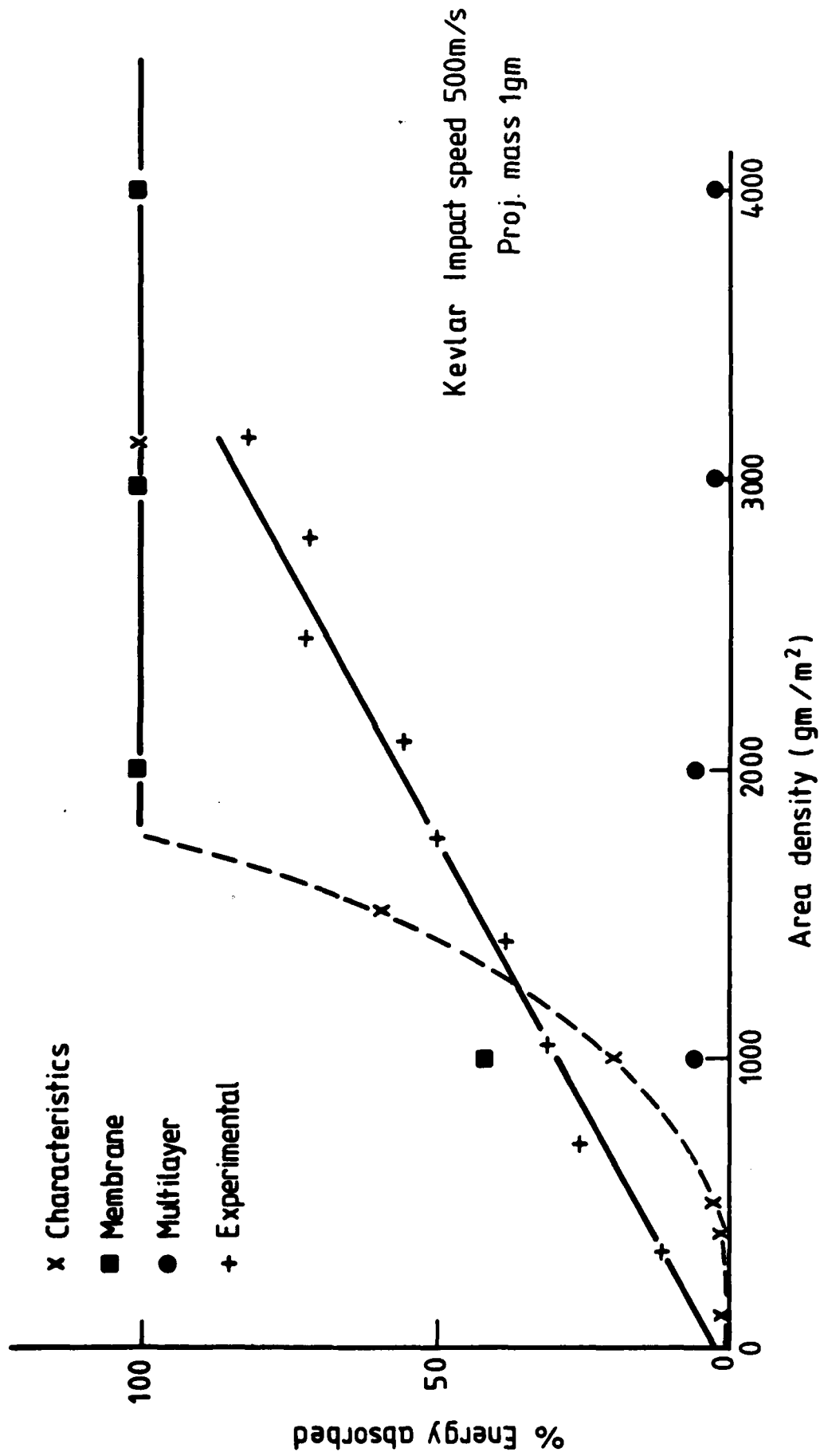
Figure 3a, shows the energies absorbed plotted against
impact velocities for different material densities for
nylon: Data does not presently exist for Kevlar.   This
together with figure 2a can yield the V_{50} for each material
since this is attained from the corner of the curve;
obviously for low velocity the projectile is stopped and
100% energy is absorbed whereas at higher velocities the
projectile passes through the fabric and emerges with lower
velocity.

Fig. 3a

Energy v impact velocity
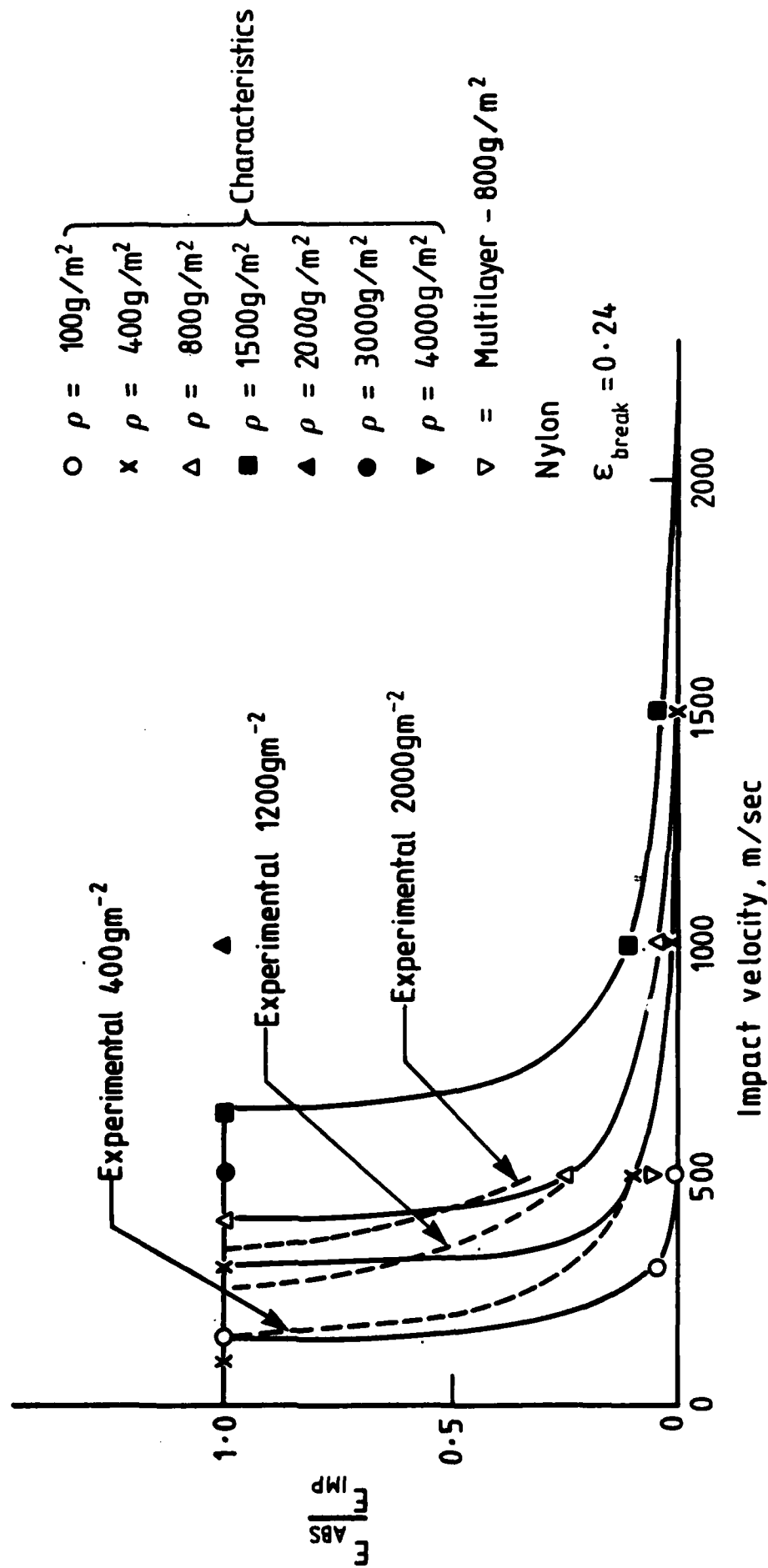
Figure 4a, b shows the variation of maximum strain and
projectile velocities at break for an impact velocity of 500
m/s for different fabric weights; for small fabric weights
the maximum strain is the breaking strain of nylon and
Kevlar respectively and the velocity at break is close to
the impact velocity. For heavy materials the velocity at
break falls off but the strain at break must still be the
breaking strain. For heavier materials which stop the
projectile the maximum strain must be less than the breaking
strain.   In the first part of these curves (penetration) it
is useful to look at the velocity at break whereas in the
later part (stopping) it is sensible to look at the maximum
strain.   These results have been obtained from the
characteristics model.
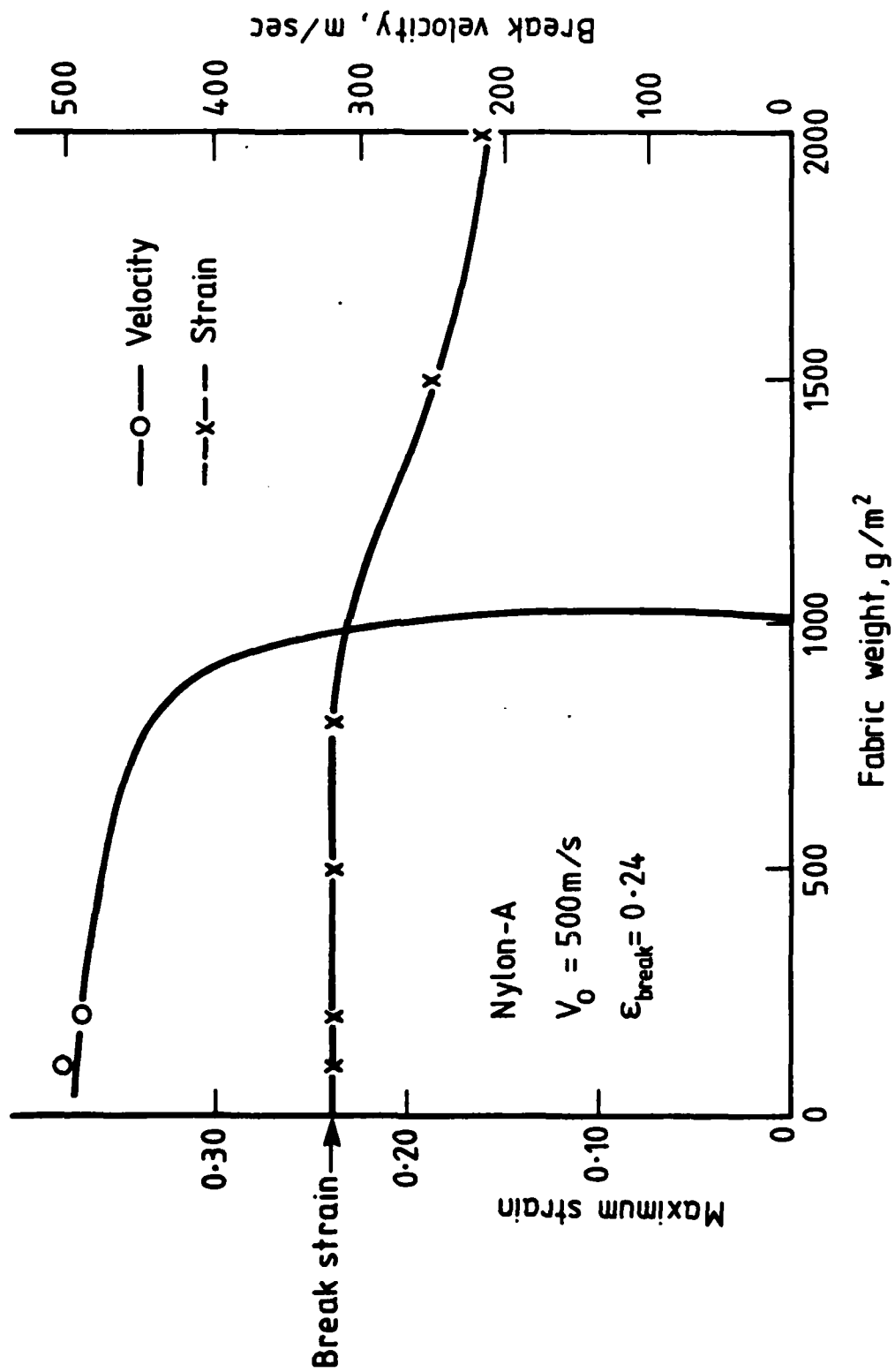
Maximum strain and break velocity vs fabric weight

Fig. 4a

Maximum strain and break velocity vs fabric weight

Fig. 4b
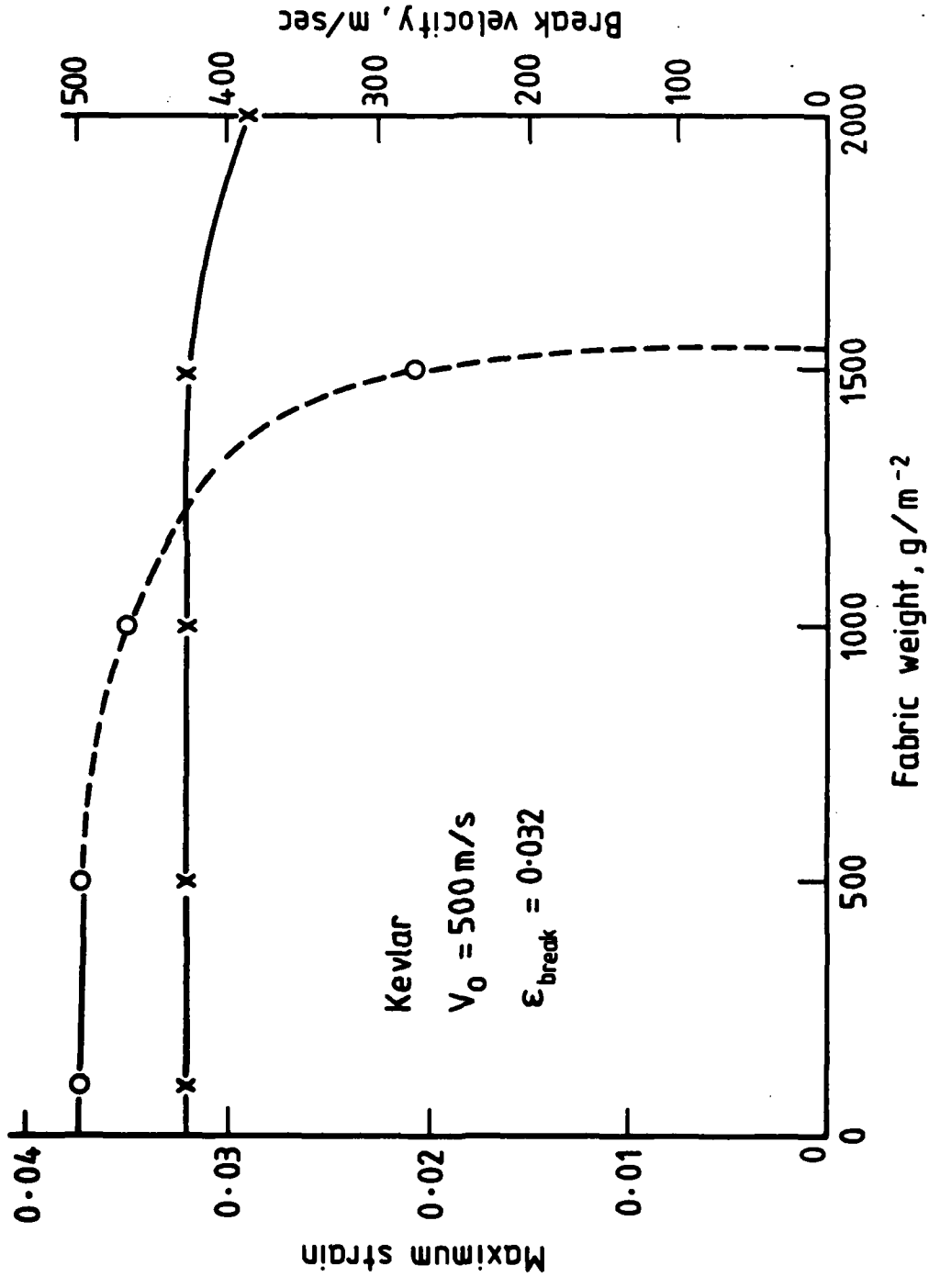
Figures 5a-e show for an impact velocity of 500 m/s and different fabric weights (Nylon, 100, 500, 1000, 1500 and 2000 gm/m^2) the variation of projectile velocity, displacement and energy and fabric fibre strain and tension with time for nylon.

Figure 5f-j show again for nylon, area densities 400 gm/m^2, the same behaviour for different impact velocities (100, 300, 500, 1000 and 2000 m/s.)

Fig. 5k-o; shows for Kevlar the same information for an impact velocity 500 m/s and for different fabric weights (100, 500, 1000, 1500 and 2000 gm/m^2).

Fig. 5 p-s; again for Kevlar shows the effect of different impact speed (500, 1000, 1500 and 2000) on fabric weight 400 gm/m^2.

BM2AAB
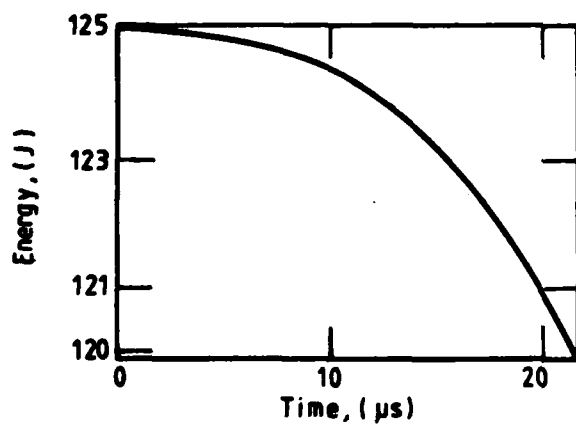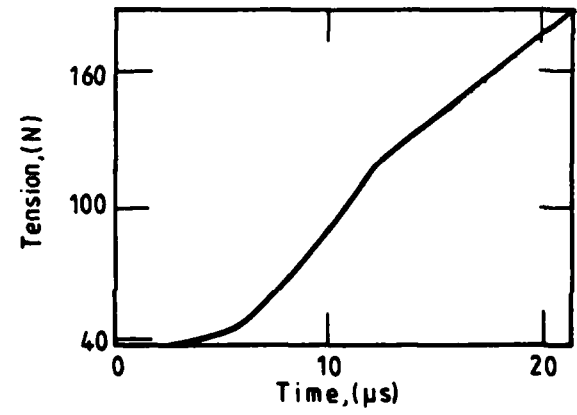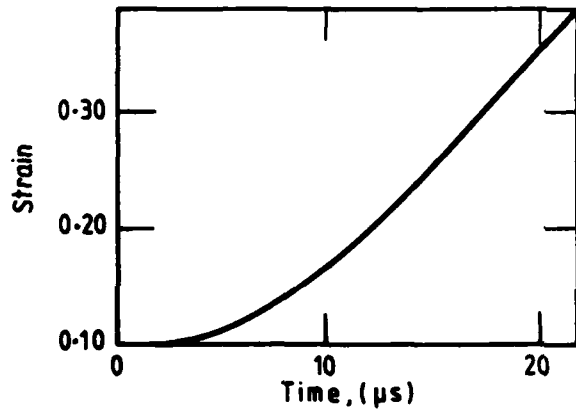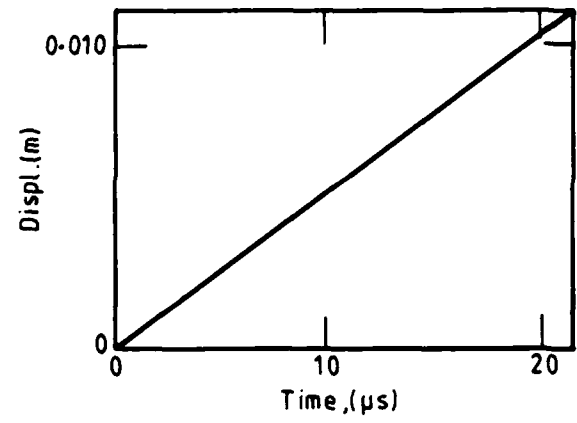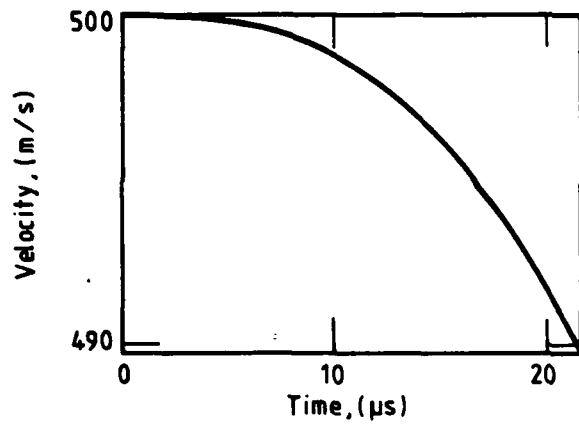
Nylon – A

$V_0 = 500 \, m/s$

$\rho = 100 \, g/m^2$

$M_0 = 1g$

B.S. = 0·24

Fig.5 (a-e)
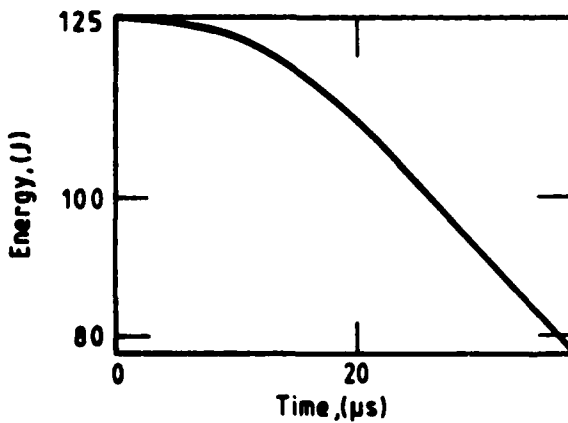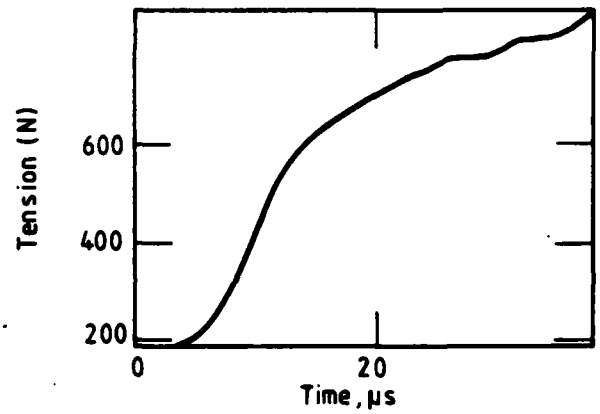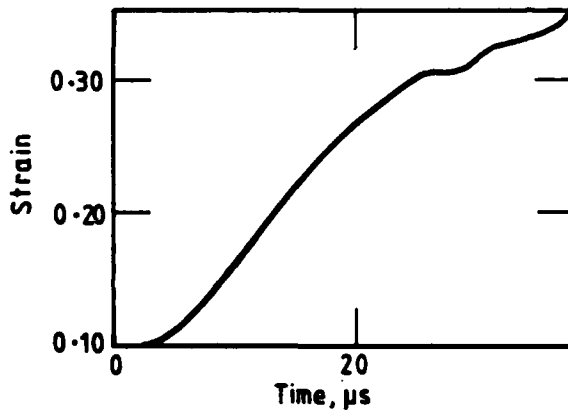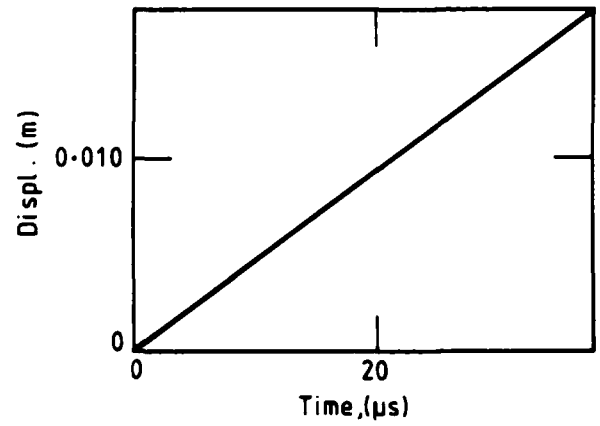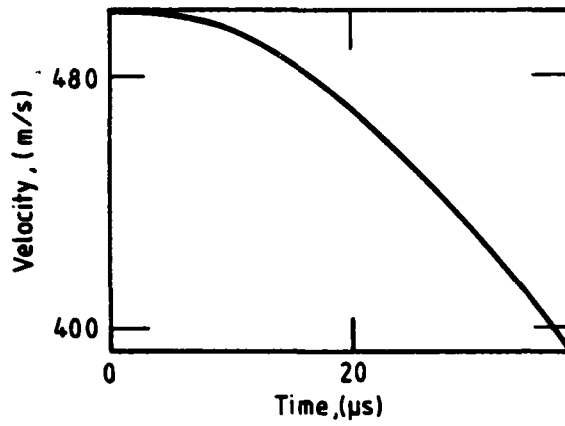
Nylon

$V_0 = 500 \, m/s$

$\rho = 500 g/m^2$

$M_0 = 1 g$

B.S. $= 0.24$

(b)
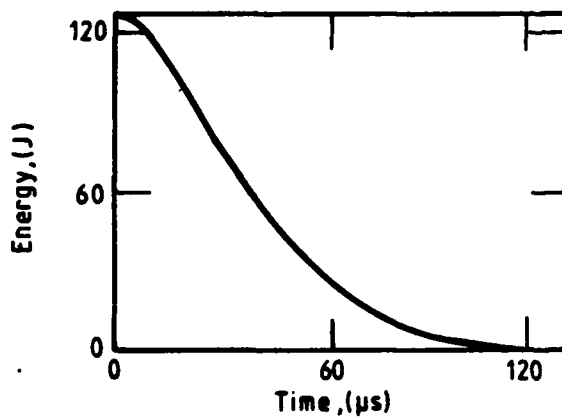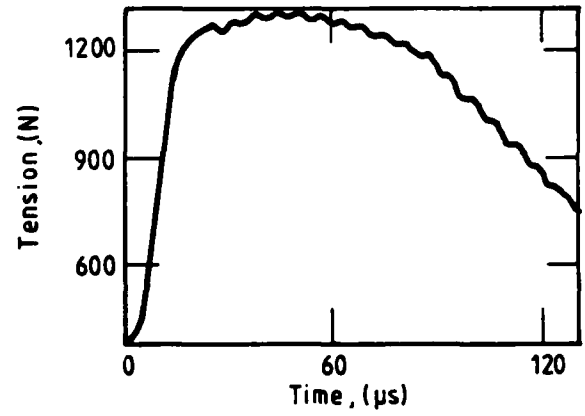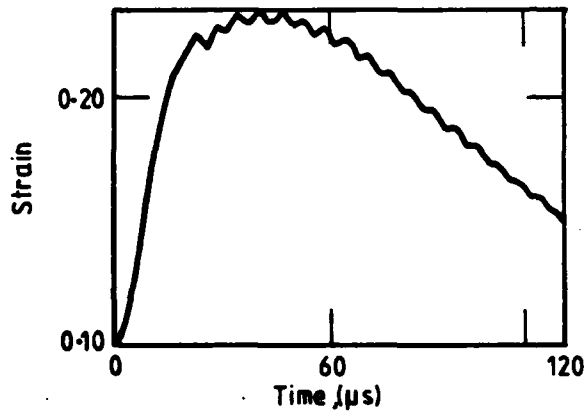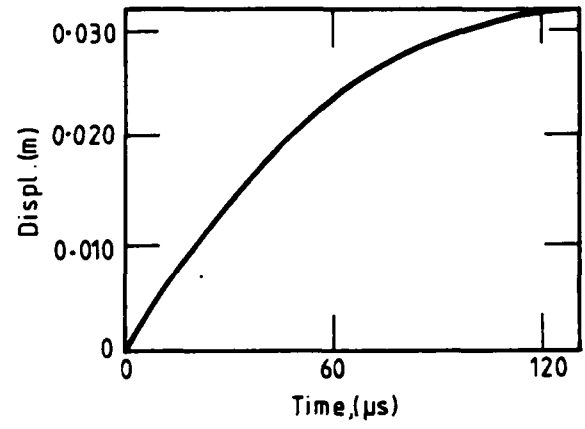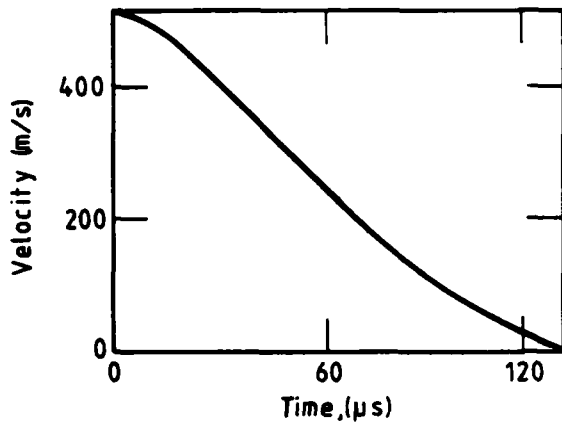
Nylon

$V_0 = 500 \text{ m/s}$

$\rho = 1000 \text{ g/m}^2$
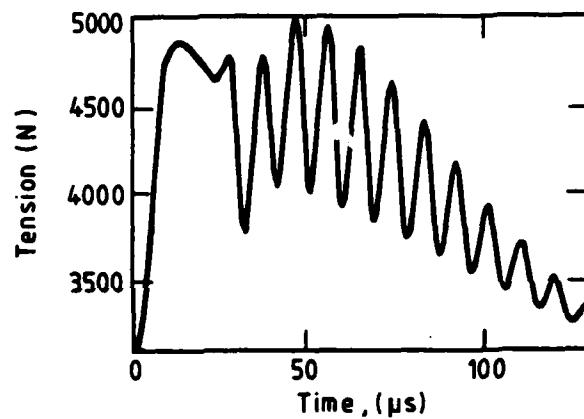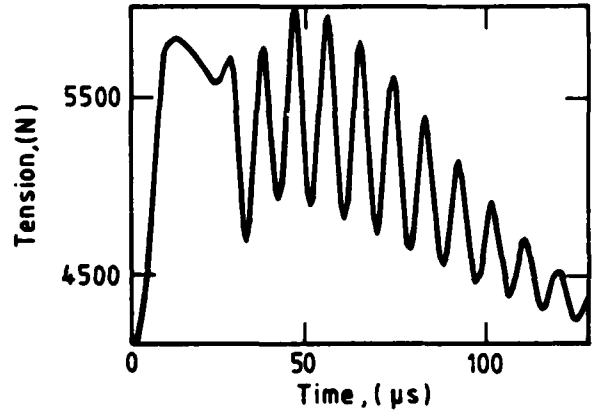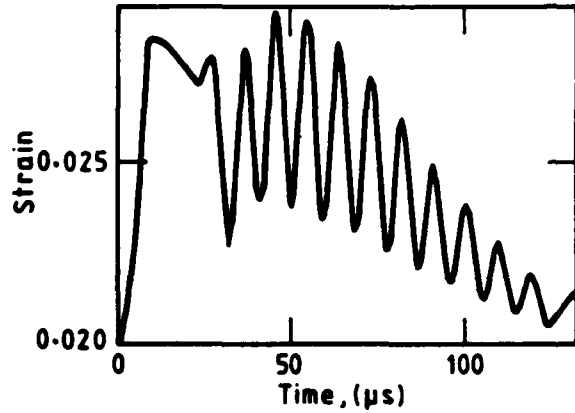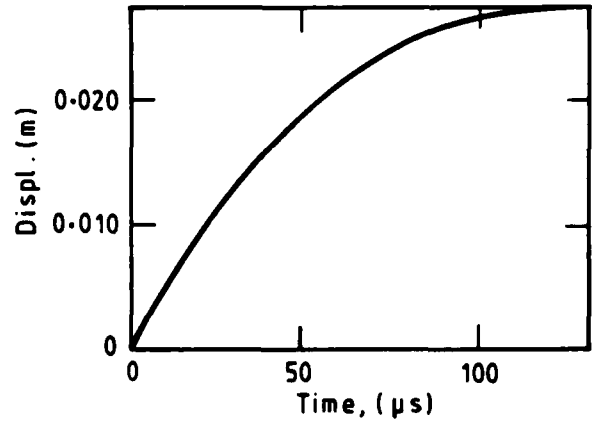
$M_0 = 1 \text{g}$

B.S.$= 0 \cdot 24$

(c)

Velocity, (m/s)

400

200

0

0   60   120
Time, (μs)

Displ. (m)

0·030

0·020

0·010

0

0   60   120
Time, (μs)

Strain

0·15

0·10

0   60   120
Time,(μs)

Tension,(N)

1200

600

0   60   120
Time, (μs)

Energy, (J)

120

60

0

0   60   120
Time, (μs)
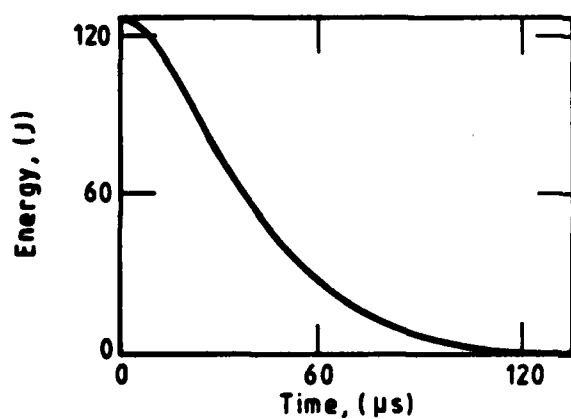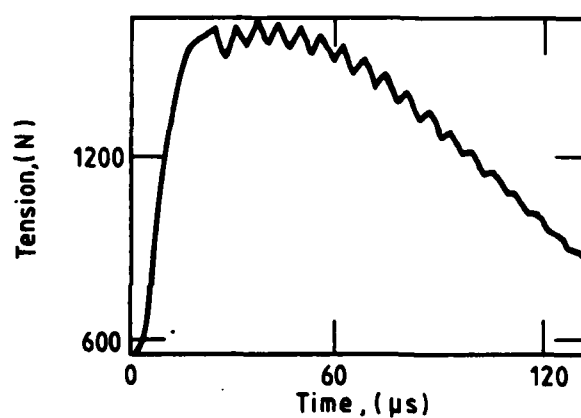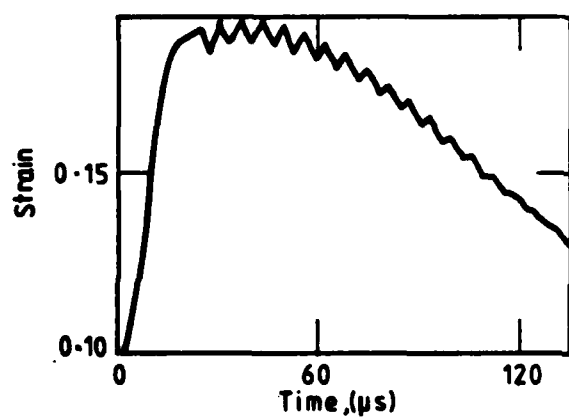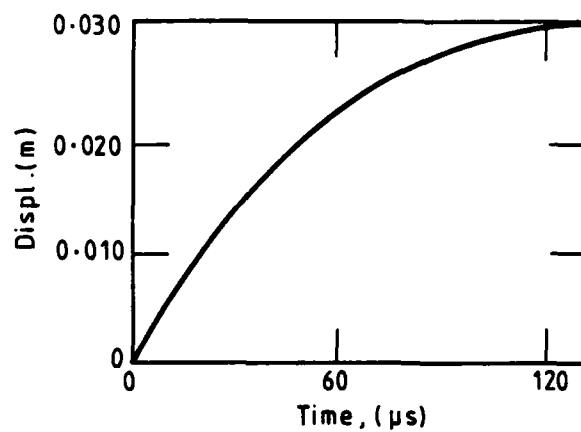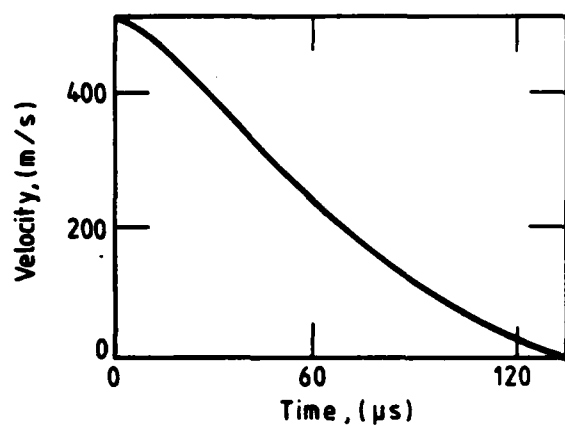
Nylon

$V_0 = 500 \, m/s$

$\rho = 1500 \, g/m^2$

$M_0 = 1g$

B.S. = 0·24

(d)
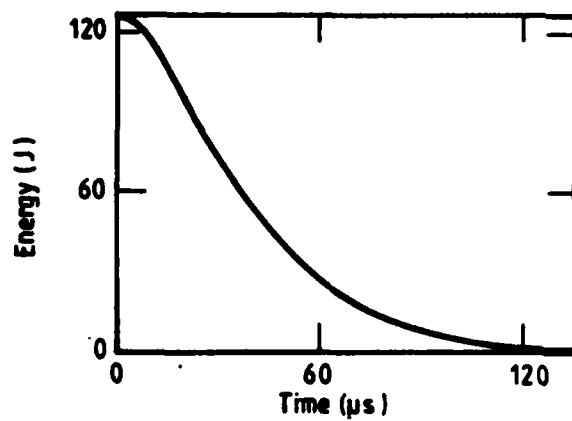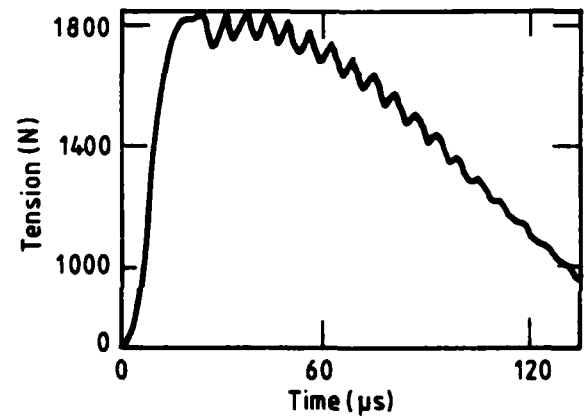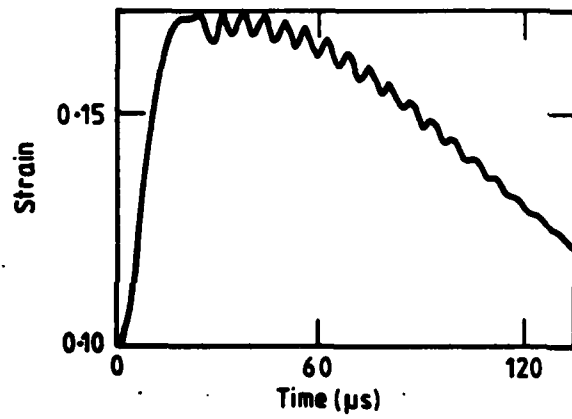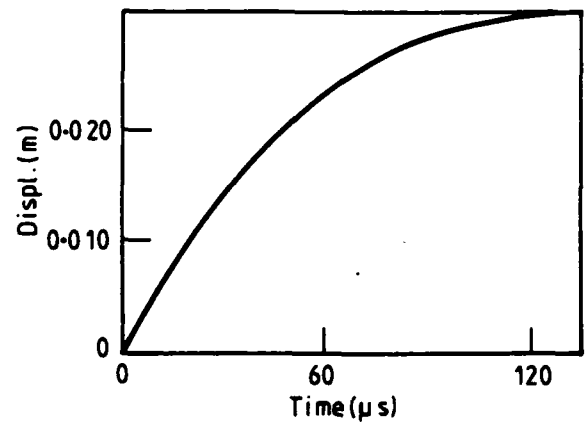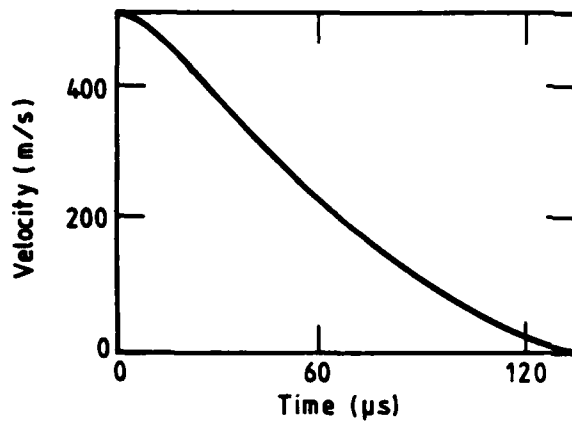
Nylon

$V_0 = 500 \, m/s$

$\rho = 2000 \, g/m^2$

$M_0 = 1 \, g$

B.S.$= 0.24$

(e)

Nylon
$V_o = 100 \, m/s$
$\rho = 400 \, g/m^2$
$M_o = 1g$
$B.S = 0.24$

Fig.5(f–j)

Nylon

$V_o = 300\,m/s$
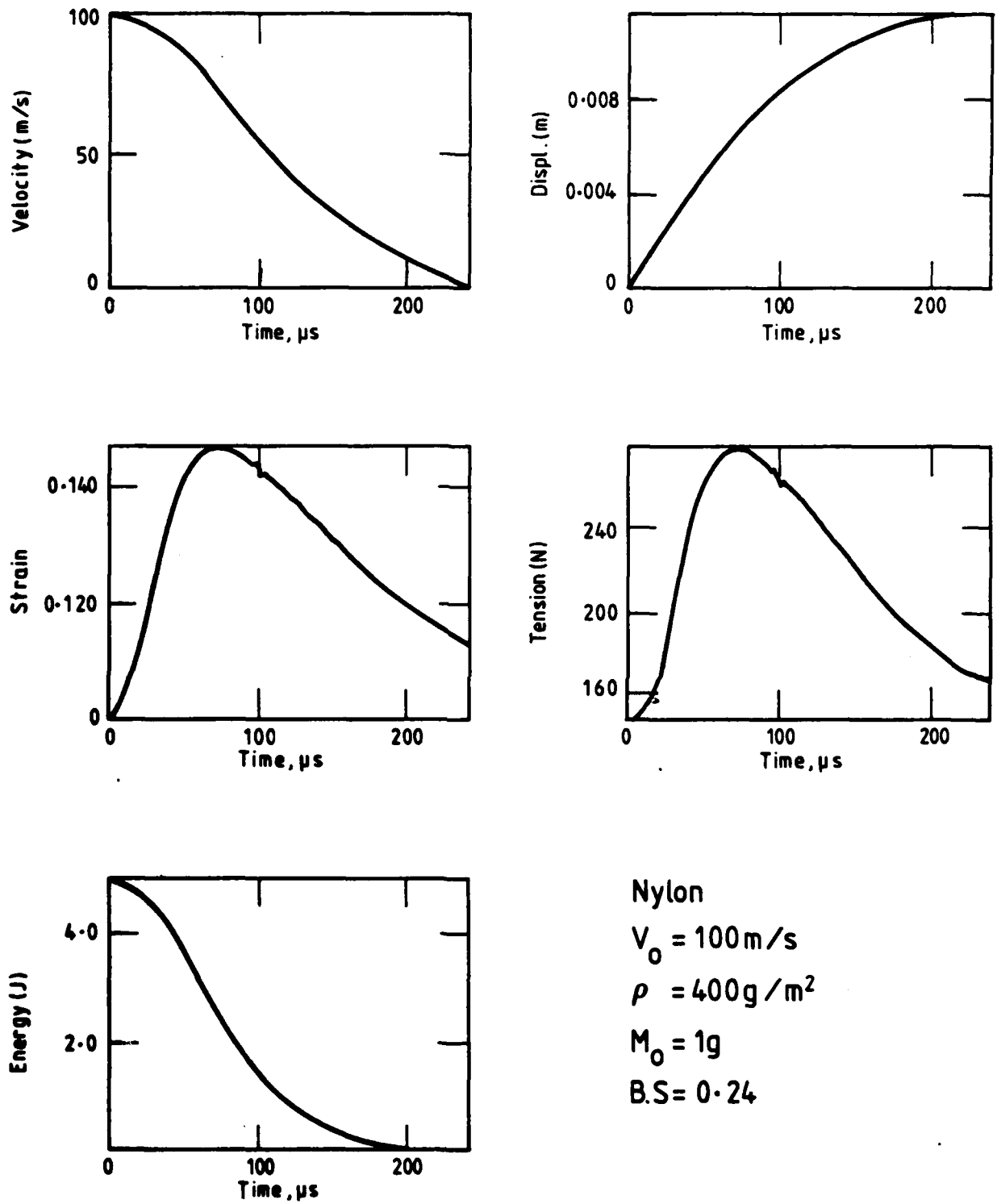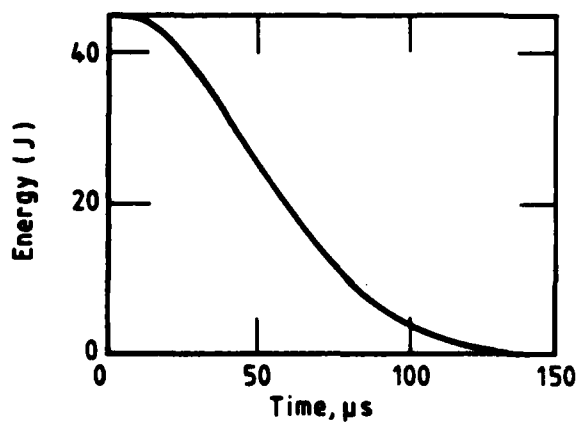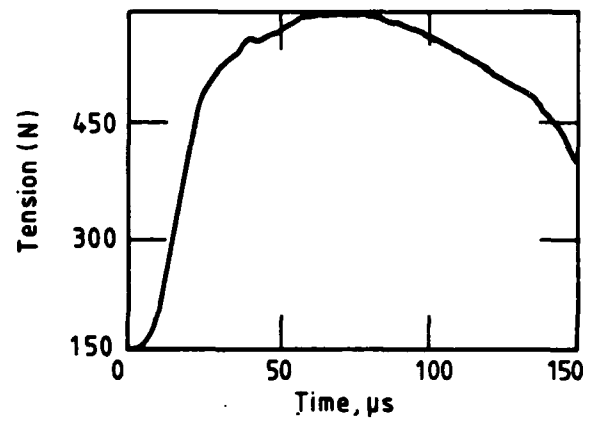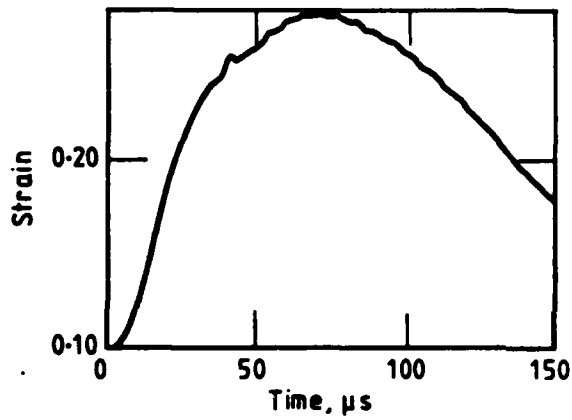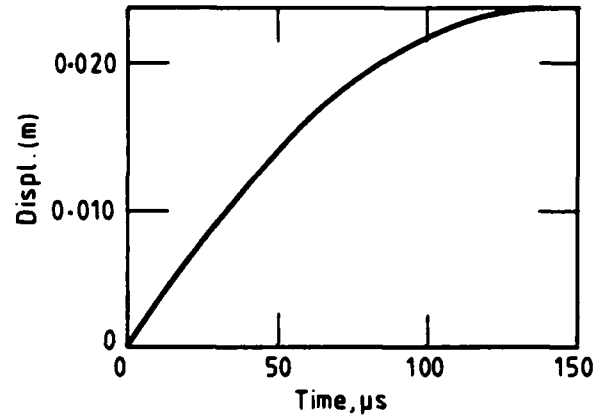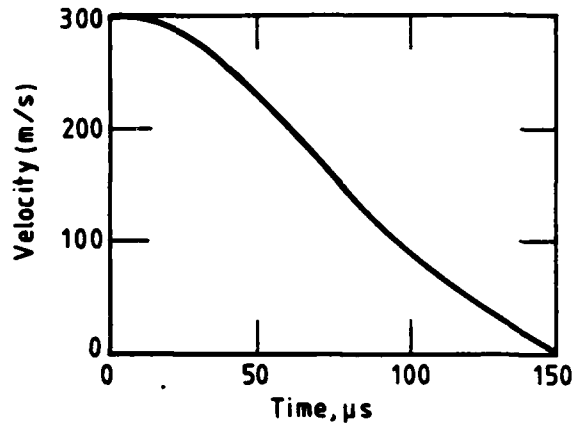
$\rho = 400\,g/m^2$

$M_o = 1g$

B.S. = 0·24

(g)
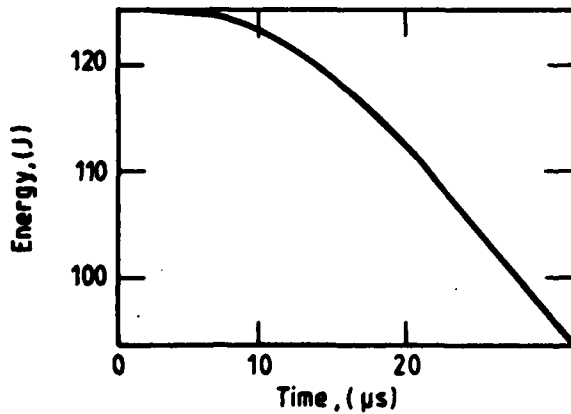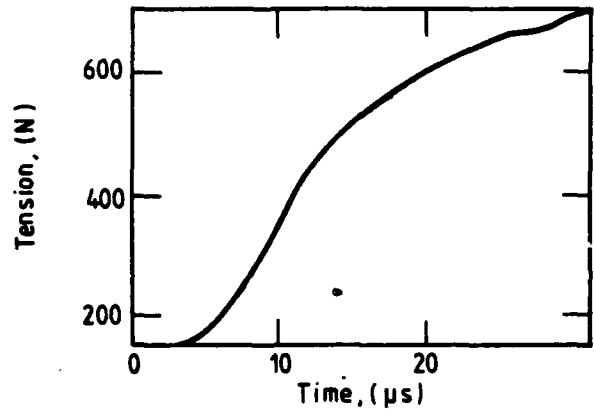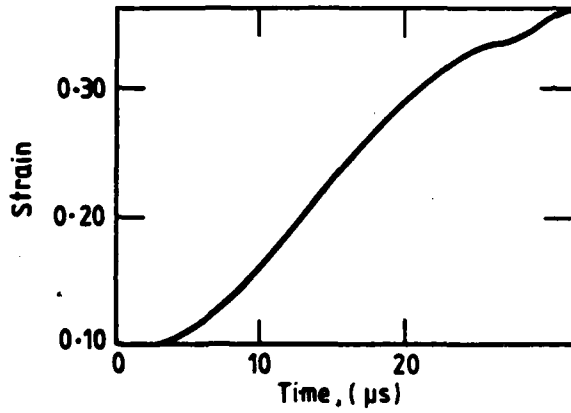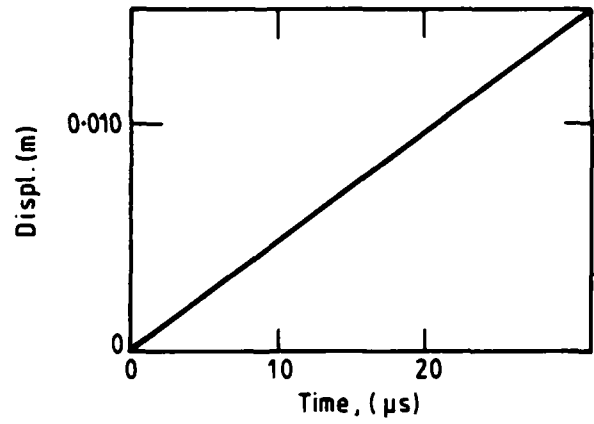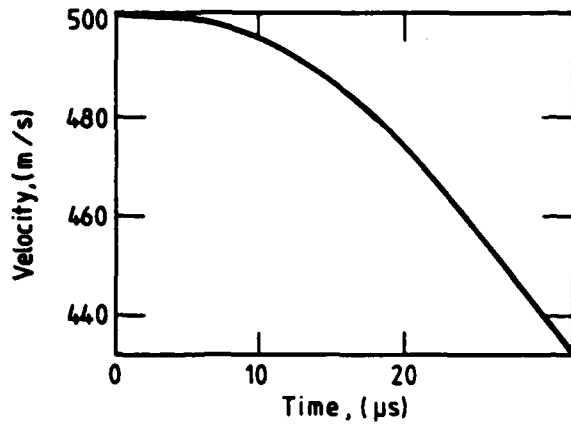
Nylon
$V_0 = 500\,m/s$
$\rho = 400\,g/m^2$
$M_0 = 1\,g$
B.S. $= 0.24$

(h)
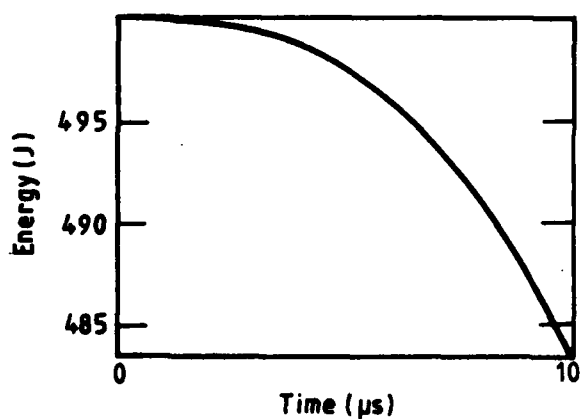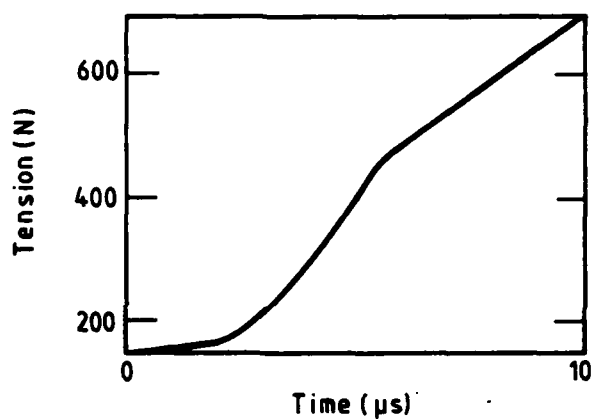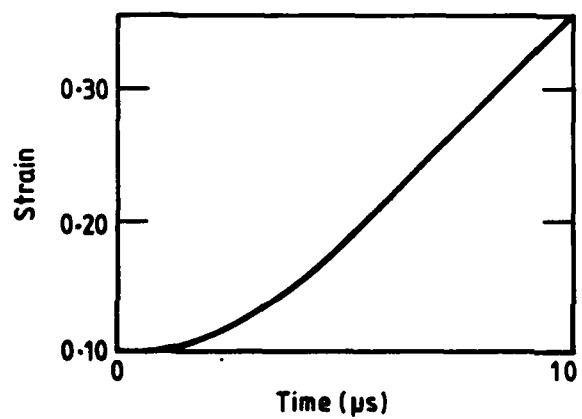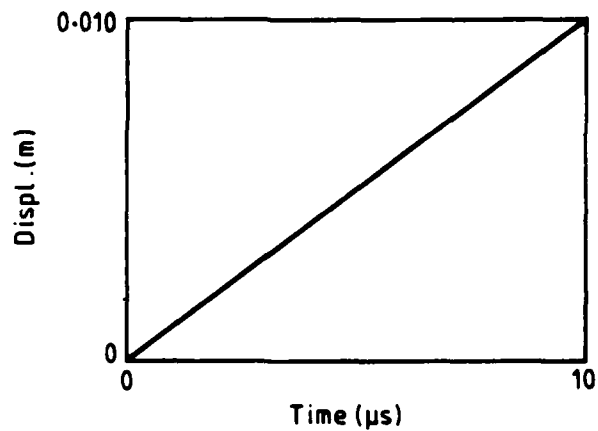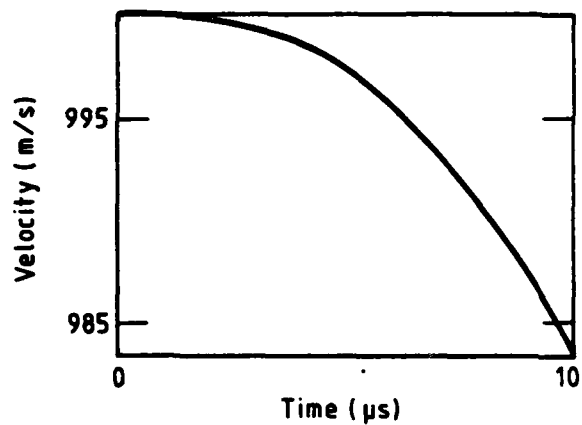
Nylon
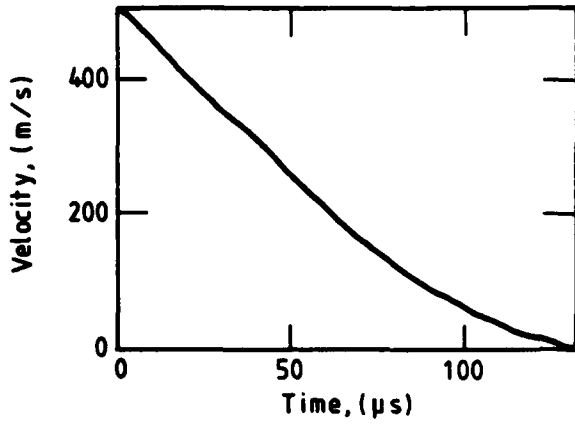$V_0 = 1000\,m/s$
$\rho = 400\,g/m^2$
$M_0 = 1\,g$
B.S.= 0·24

(i)
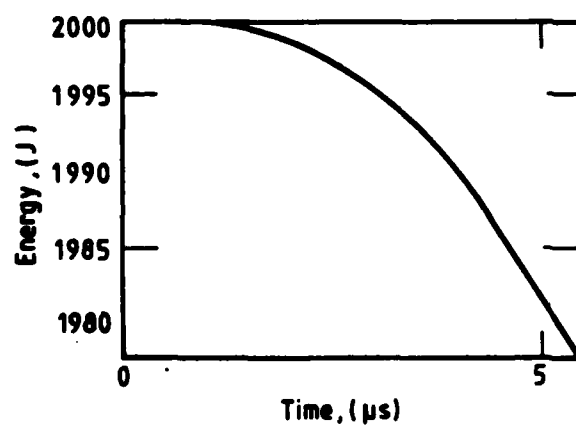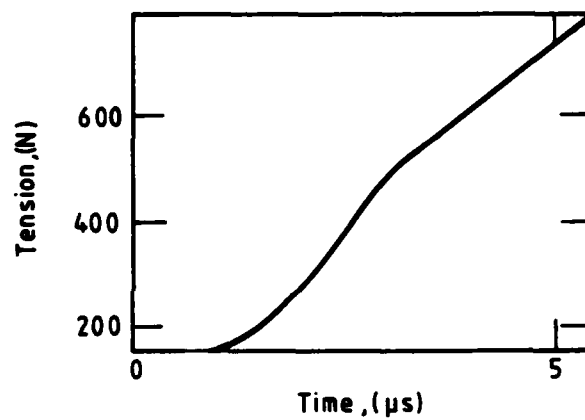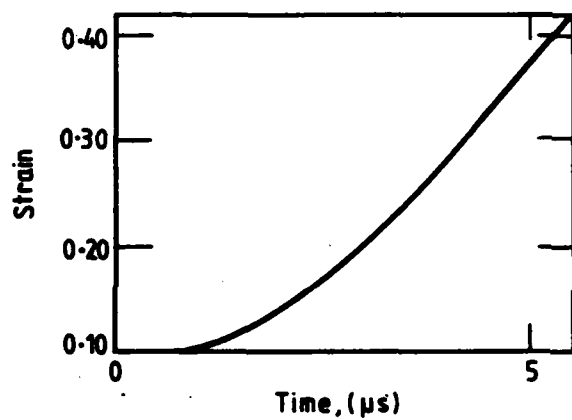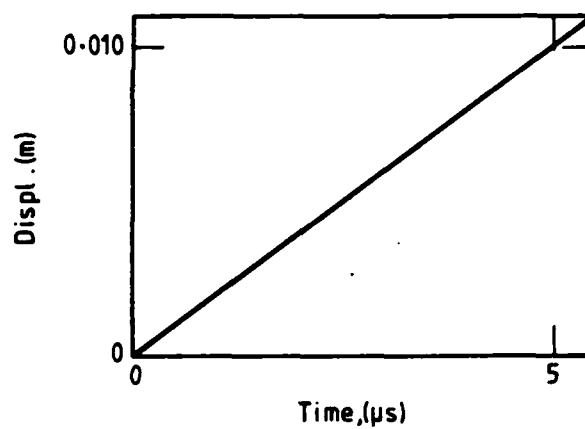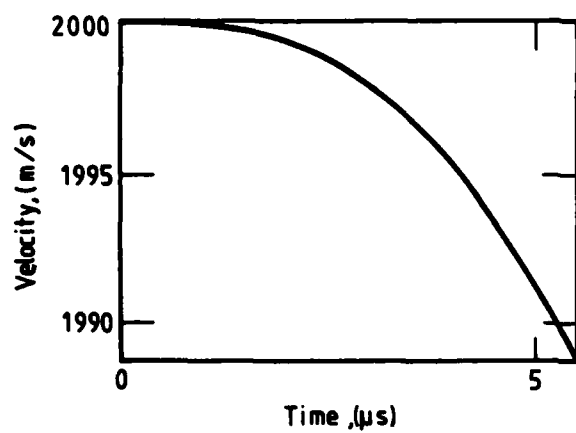
Nylon

$V_0 = 2000 \text{ m/s}$

$\rho = 400 \text{g/m}$

$M_0 = 1 \text{g}$

B.S. $= 0.24$
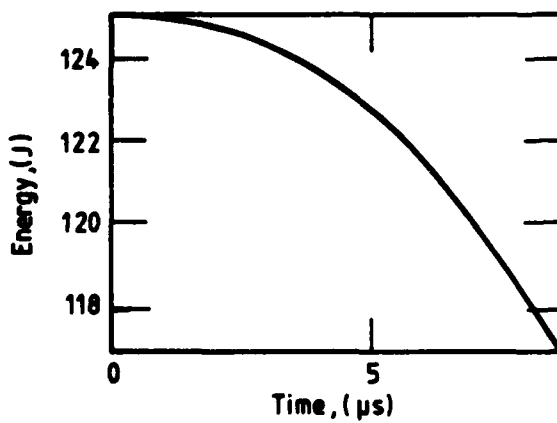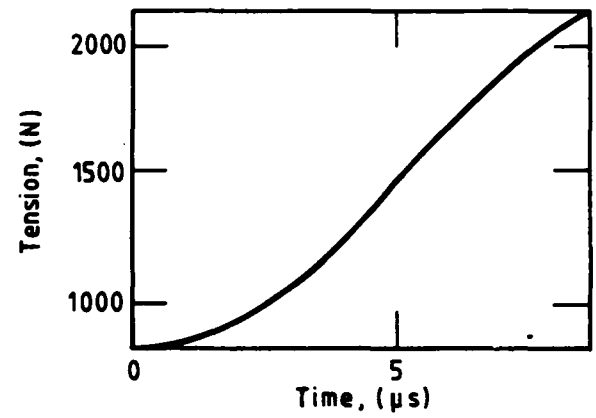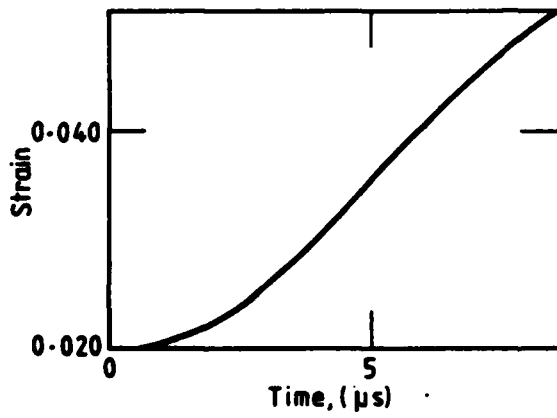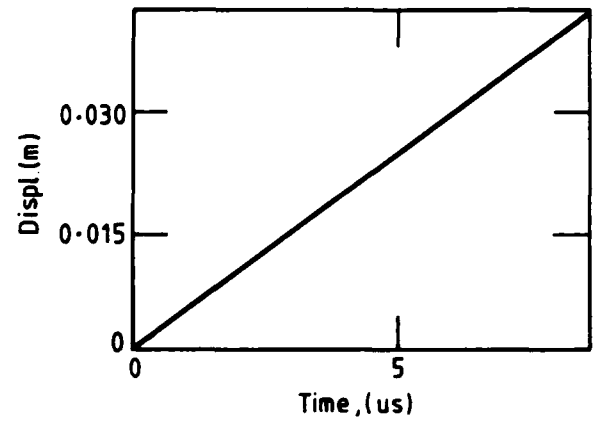
(j)
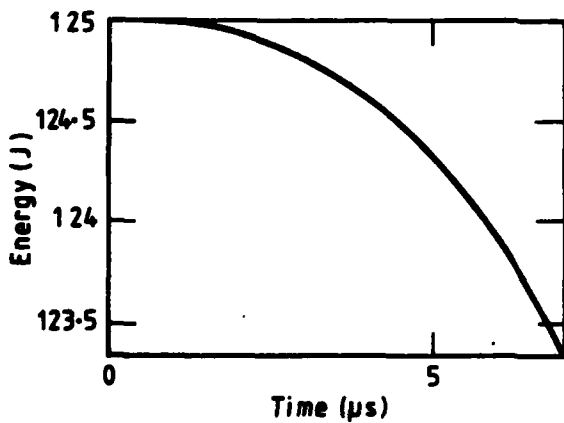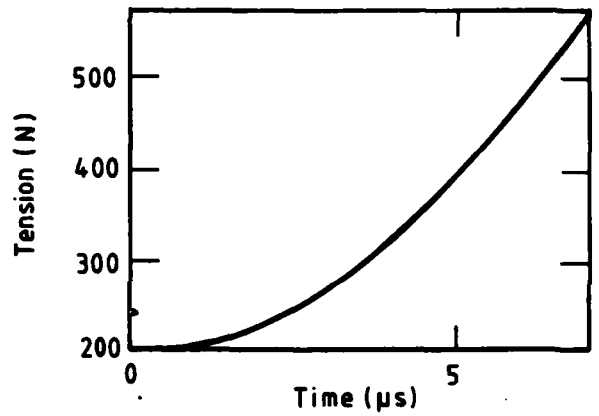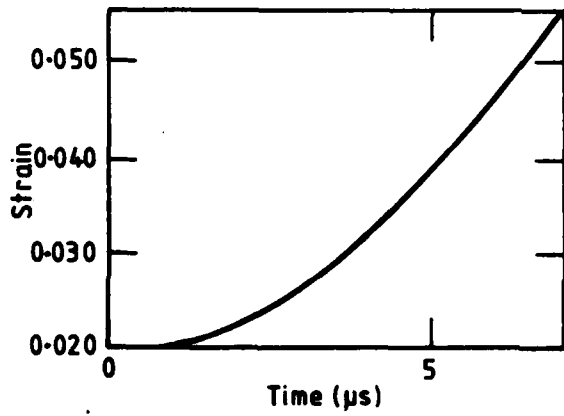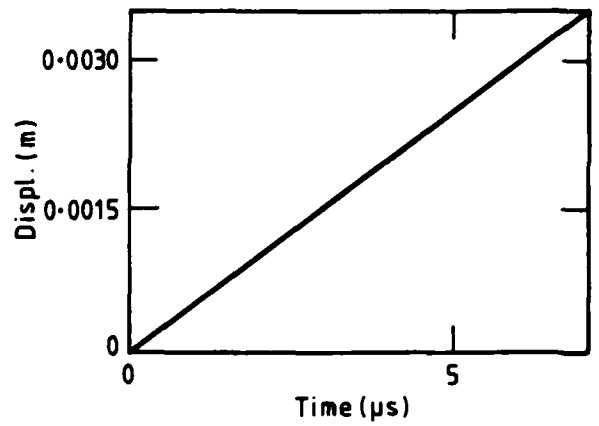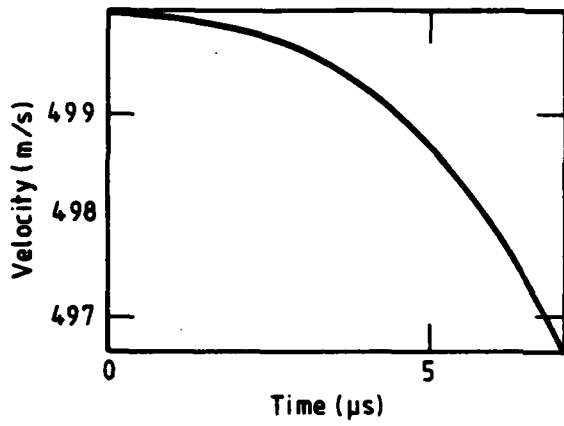
Kevlar

$V_0 = 500 \, m/s^{-1}$

$\rho = 100 \, g/m^2$

$M_0 = 1g$

B.S. = 0·032

Fig. 5 (k-o)
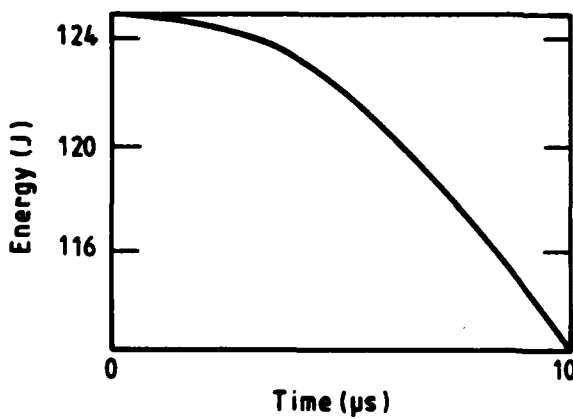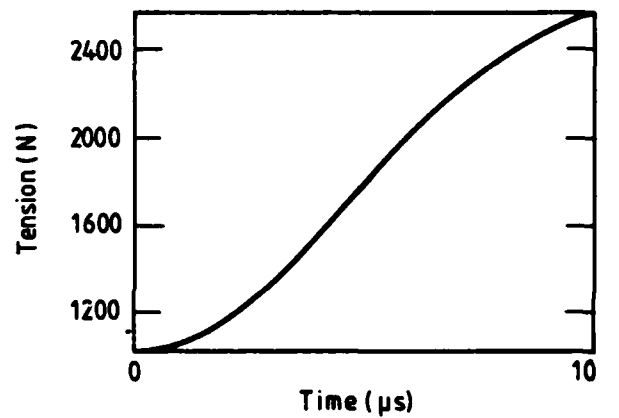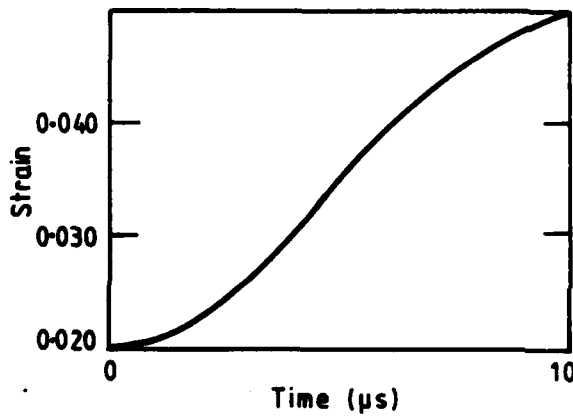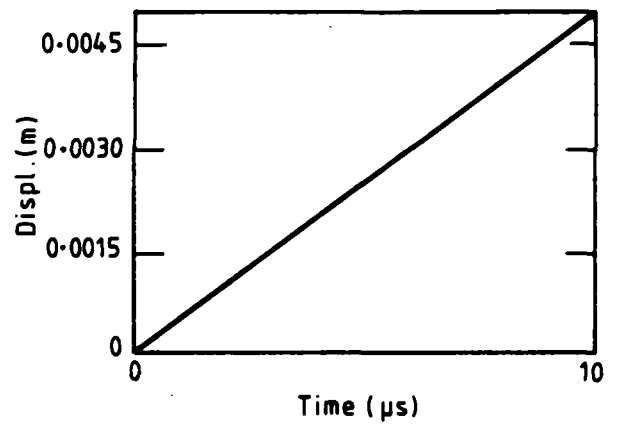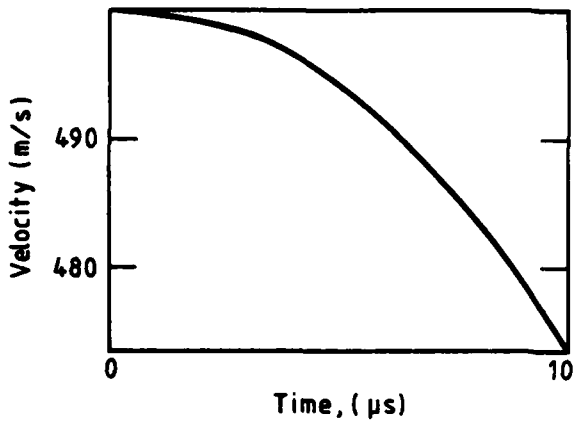
Kevlar

$V_0 = 500\,m/s$

$\rho = 500\,g/m^{-2}$

$M_0 = 1\,g$

B.S. $= 0.032$

(L)
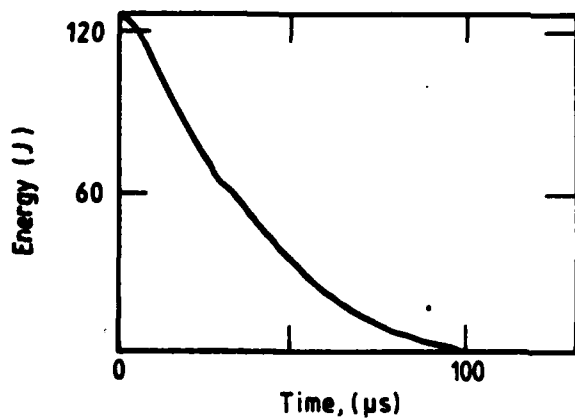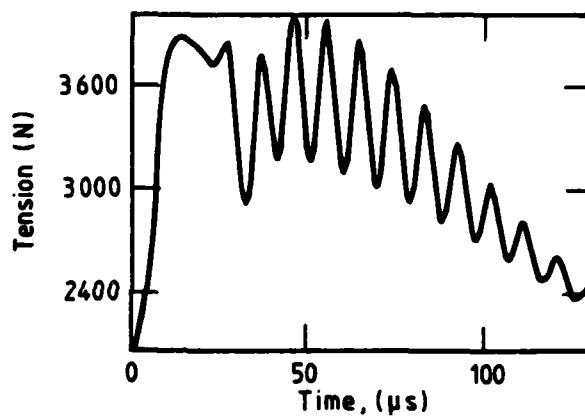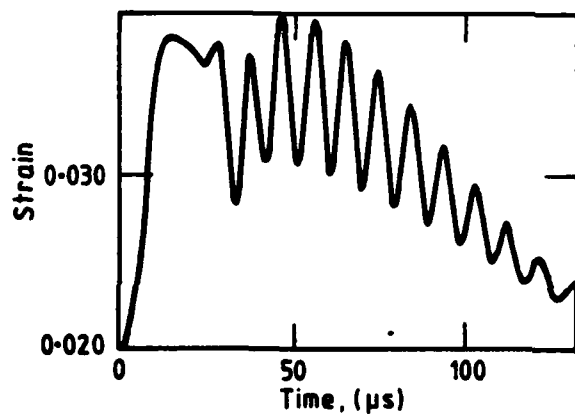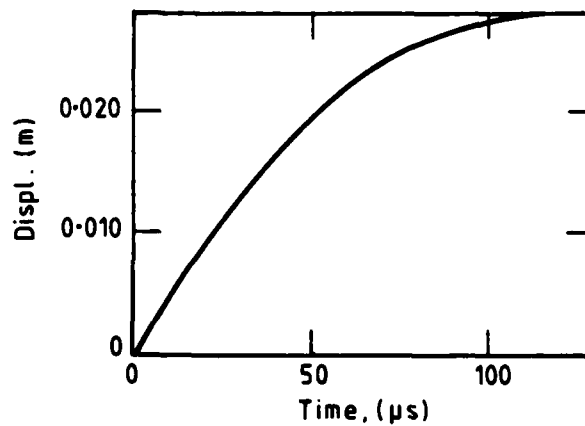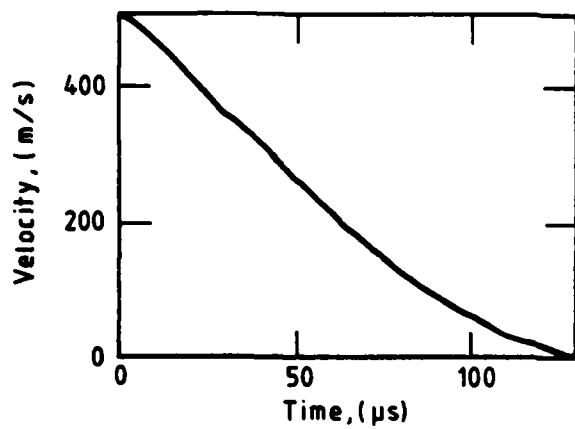
Kevlar

$V_0 = 500 \, m/s$

$\rho = 1000 \, g/m$

$M_0 = 1 \, g$

$B.S. = 0.032$

(m)
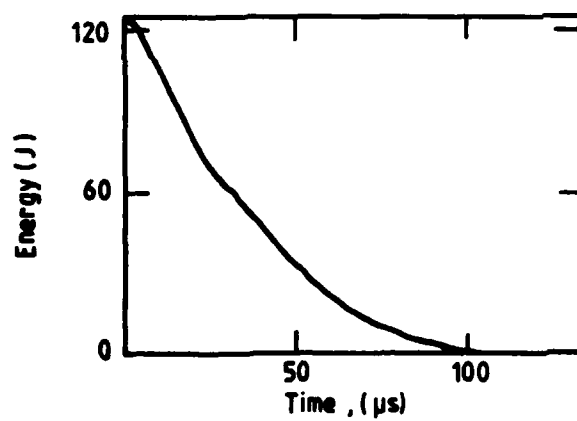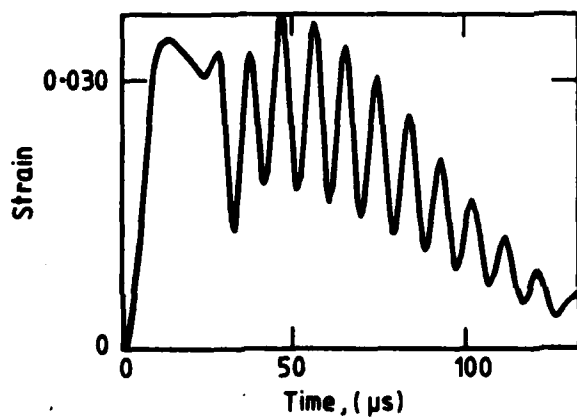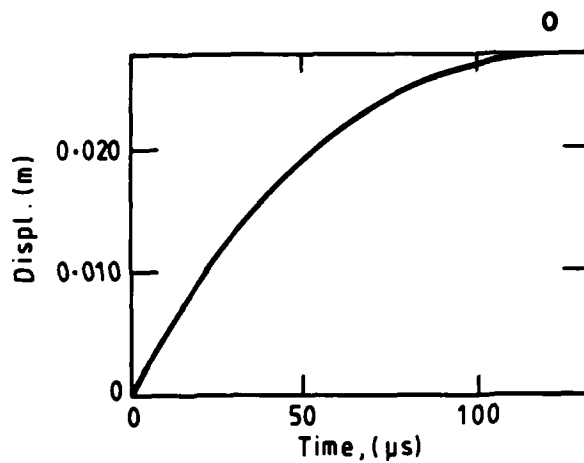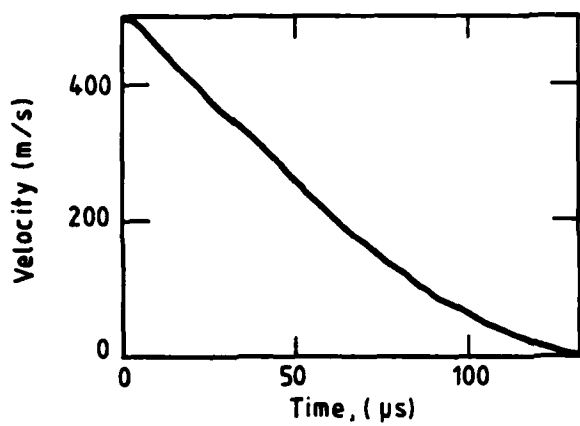
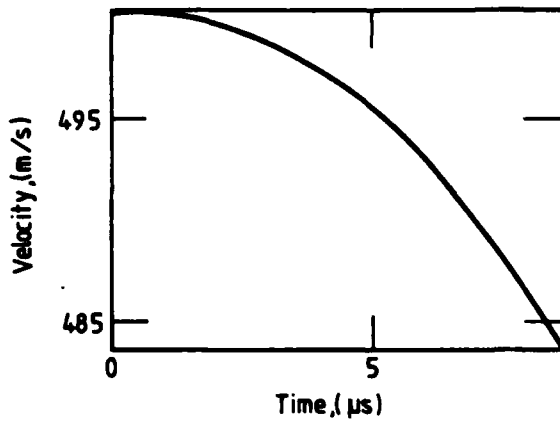Kevlar

$V_0 = 500 \, m/s$

$\rho = 1500 \, g/m^2$

$M_0 = 1g$

B.S. $= 0.032$

(n)
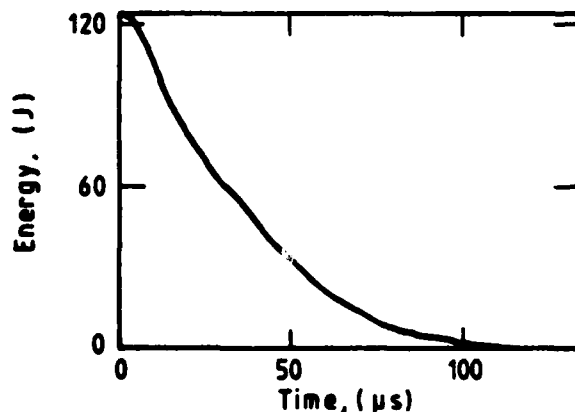
Kevlar

$V_0 = 500\,\text{m/s}$

$\rho = 2000\,\text{g/m}^2$
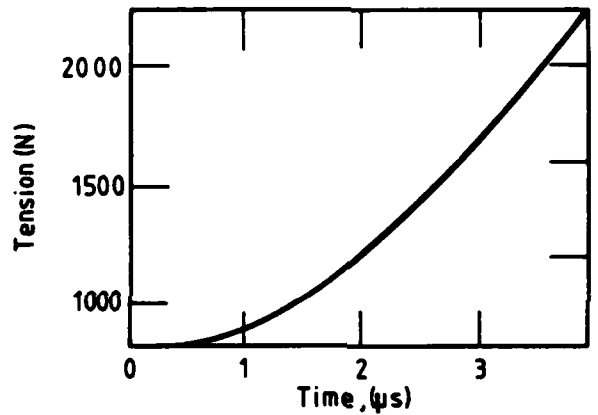
$M_0 = 1\,\text{g}$

B.S. = 0·032

(o)

Kevlar
$V_0 = 500\,m/s$
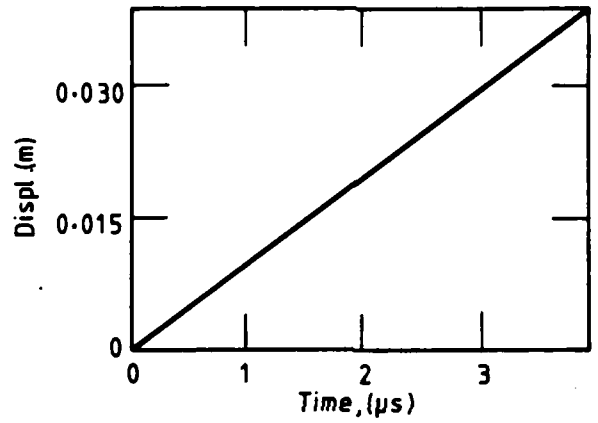$\rho = 400\,g/m^2$
$M_0 = 1\,g$
$B.S. = 0.032$

Fig. 5 (p-s)
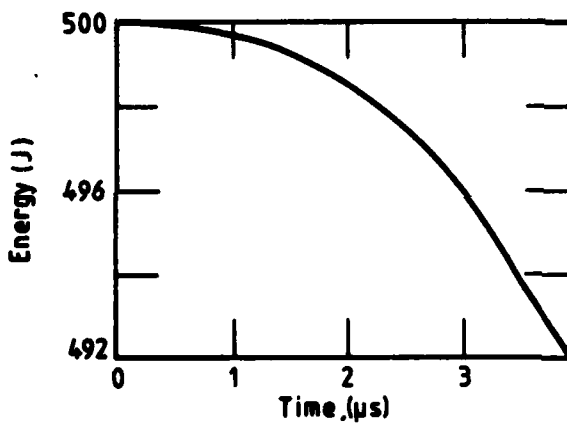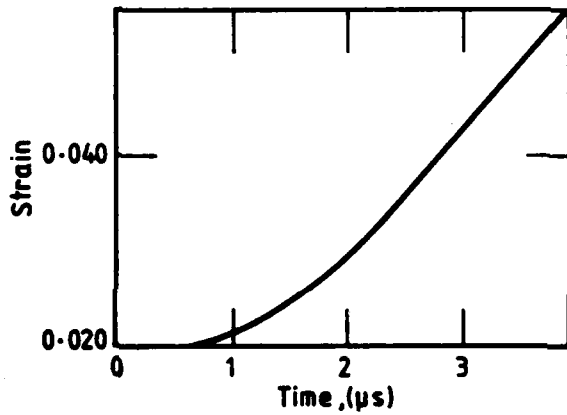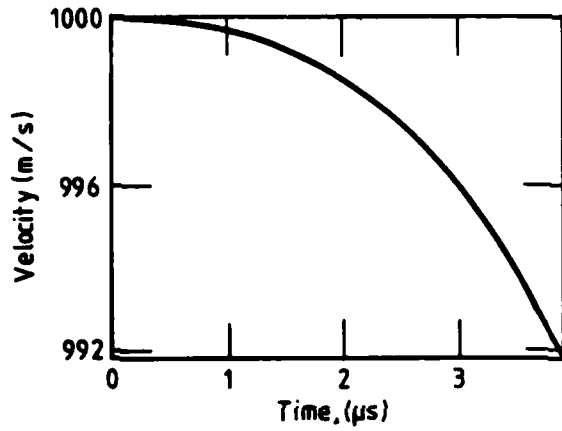
Kevlar

$V_0 = 1000 \, m/s$

$\rho = 400 g/m^2$

$M_0 = 1g$

B.S. $= 0 \cdot 032$

(q)
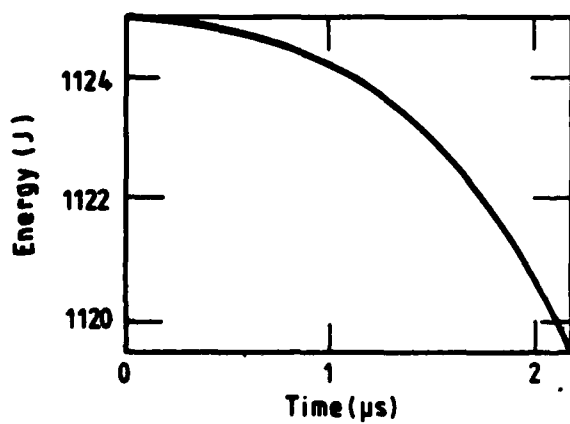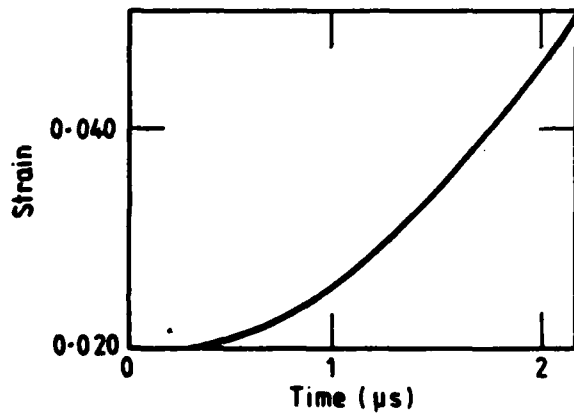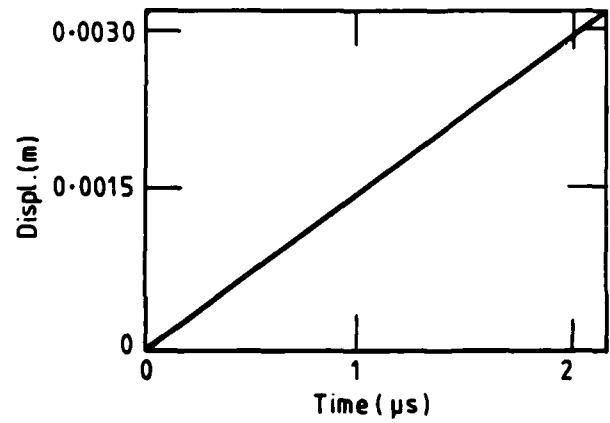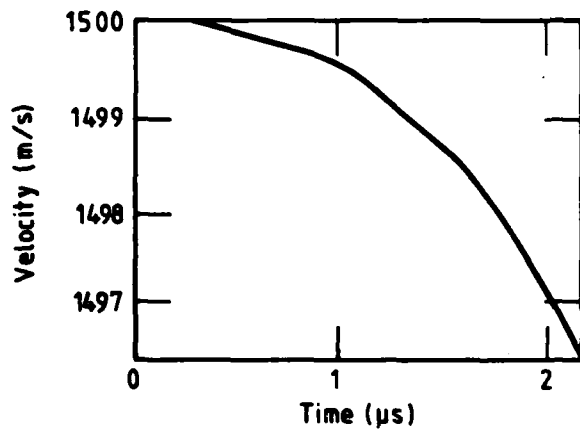
Kevlar

$V_0 = 1500 \, m/s$

$\rho = 400 \, g/m^2$

$M_0 = 1g$

B.S.= 0·032 ,

(r)

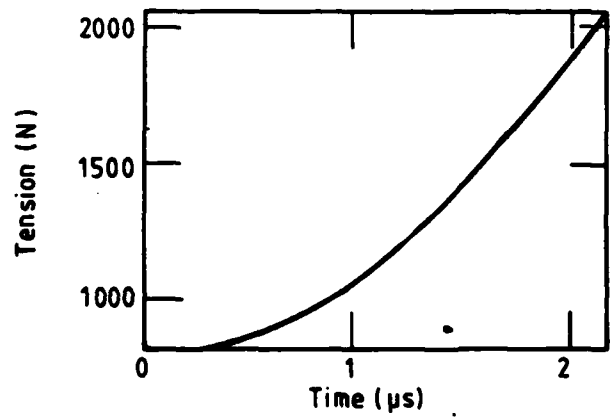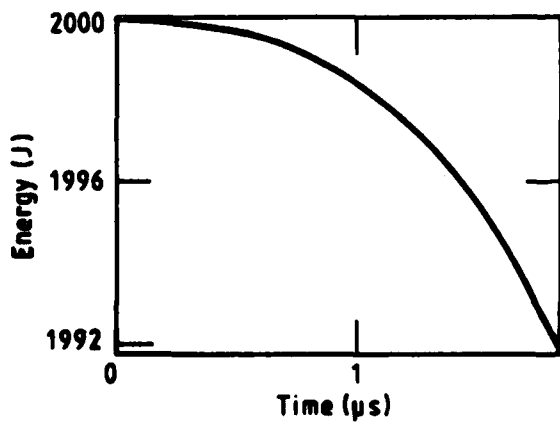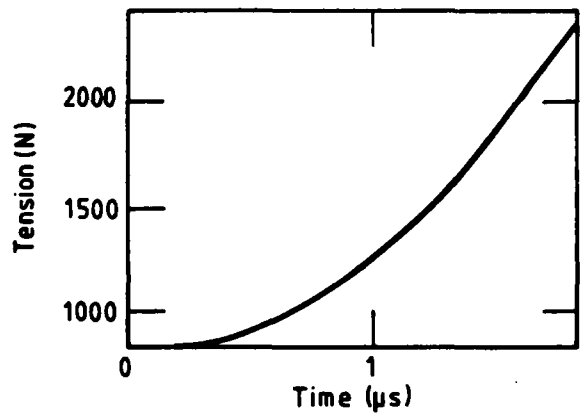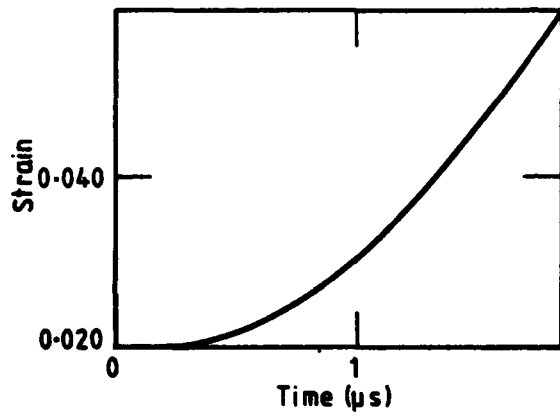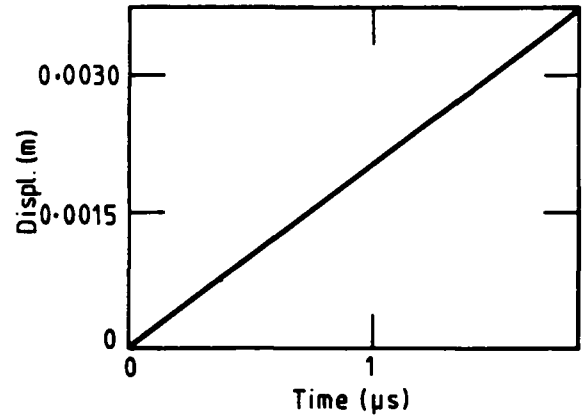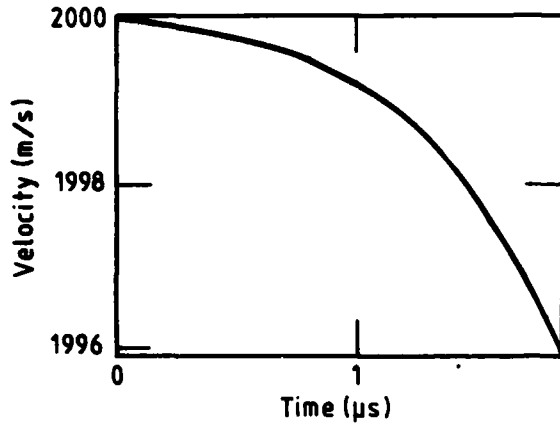Kevlar

$V_0 = 2000 \, m/s$

$\bar{\rho} = 400 \, g/m^2$

$M_0 = 1g$

B.S. $= 0 \cdot 032$

(s)

Figures 6 a, b show typical multiflash views of fabrics under impact. The photographs show a side view of impact; the projectile travels from bottom to top in each case. The minor divisions visible in figure 6a(c) are 0.5mm.

Figures 6c,d,e,f, show the variation in pyramid height with time for both nylon (figs.6a and 6b) and for Kevlar (figs.6c and 6d). These experimental results are compared to the characteristics model (figs.6c and 6e) and to the membrane model (figs.6d and 6f).

The observed failure of the fabric is shown by the termination of the experimental plot. Similarly the theoretical failure points are also shown.

Figure 6 g, h are plots of the distance of the traverse wave from the centre of impact vs time.

Fig. 6i is a plot of pyramid height vs the traverse wave displacement. These are shown to be related linearly.

Legend for Figure 6a (overleaf)

Side views of impacted fabrics at 10, 20, 30 and 40 μs after impact.

Normal Area Density (g m^{-2})	Nylon	Kevlar
1000		D
2000	A	E
3000	B	F
4000	C	G
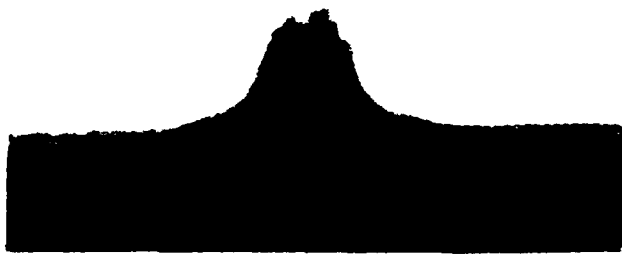
A

B
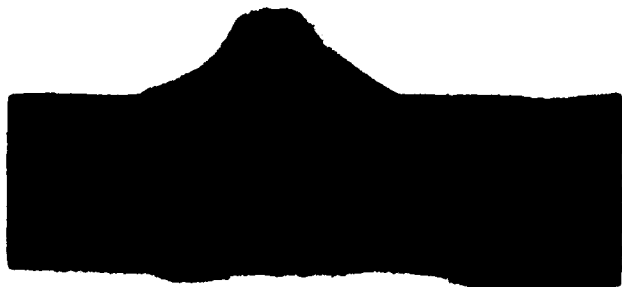
D

E
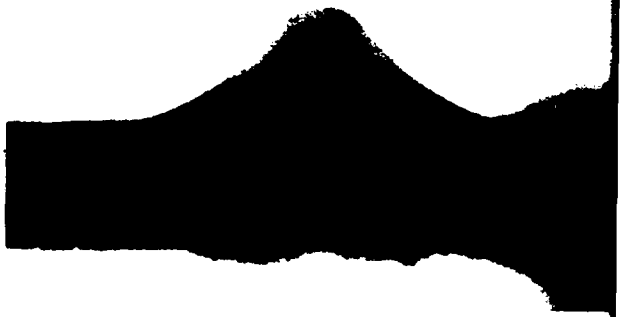
F
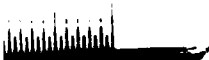
Legend for Figure 6b (overleaf)

Side views of impacted fabrics at various times after impact chosen to show penetration (the 4000 g m^{-2} Kevlar was not penetrated).

Nominal Area Density (g m^{-2})	Nylon	Kevlar
1000		D
2000	A	E
3000	B	F
4000	C	G

D

A

E

B

F

Fig. 6c
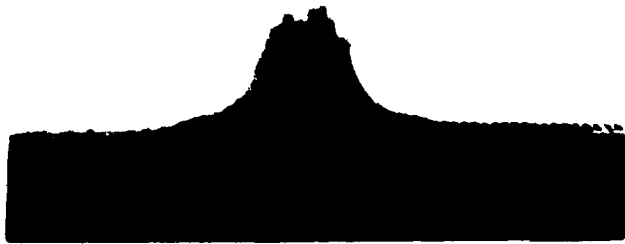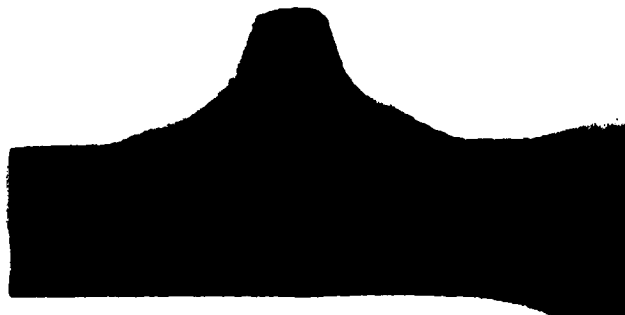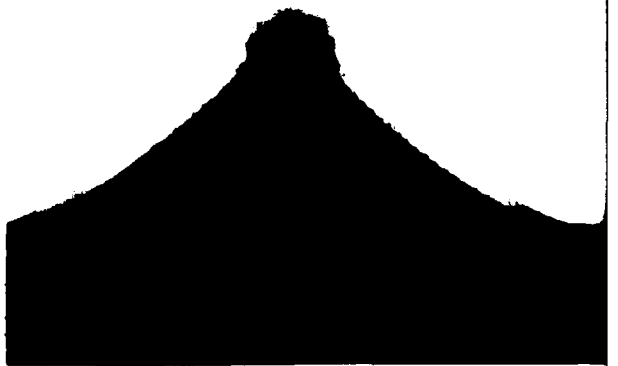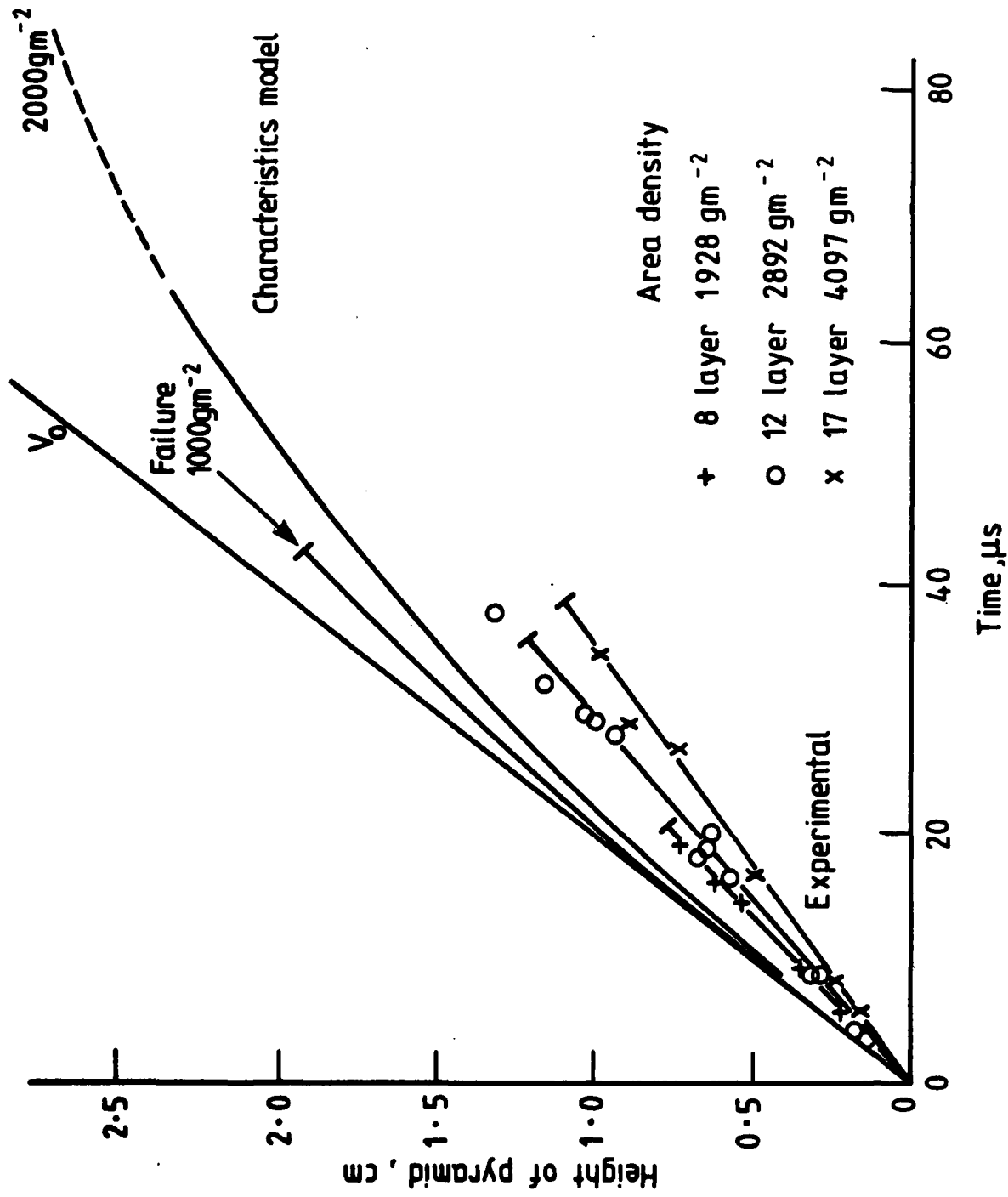
Pyramid height against time for multi-layered nylon

Pyramid height against time for multi-layered nylon

Fig. 6d

Pyramid height against time for multi-layered kevlar

Fig. 6e

53

Fig.6f
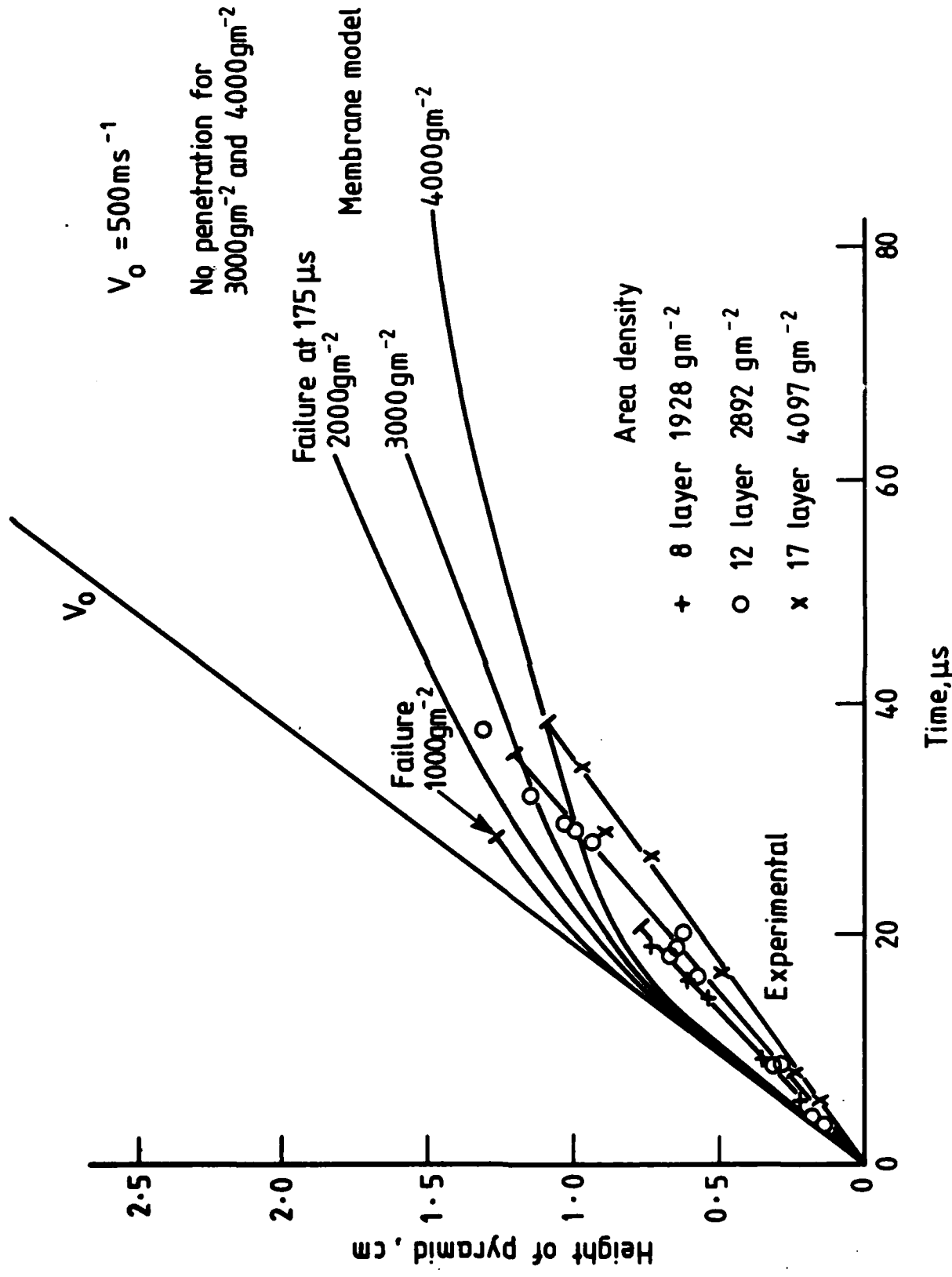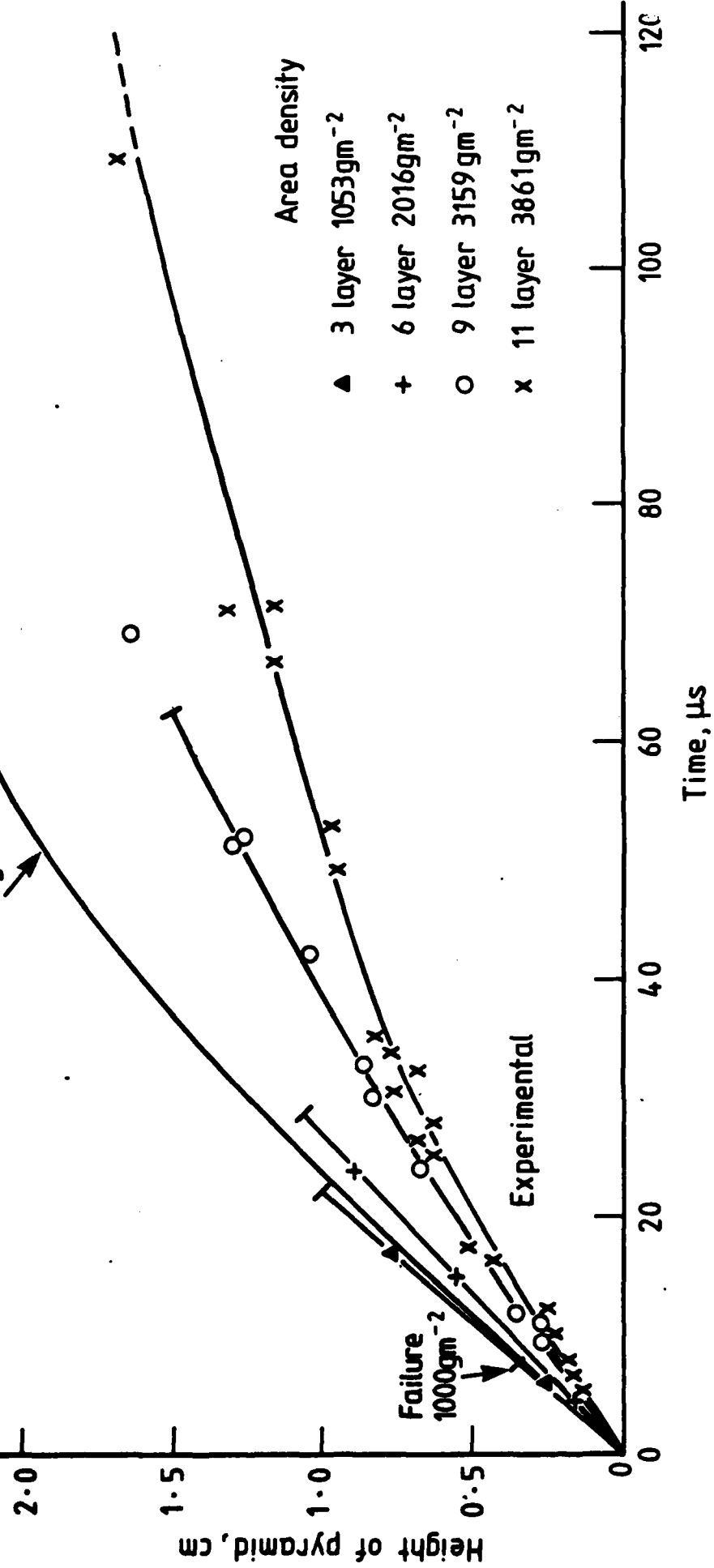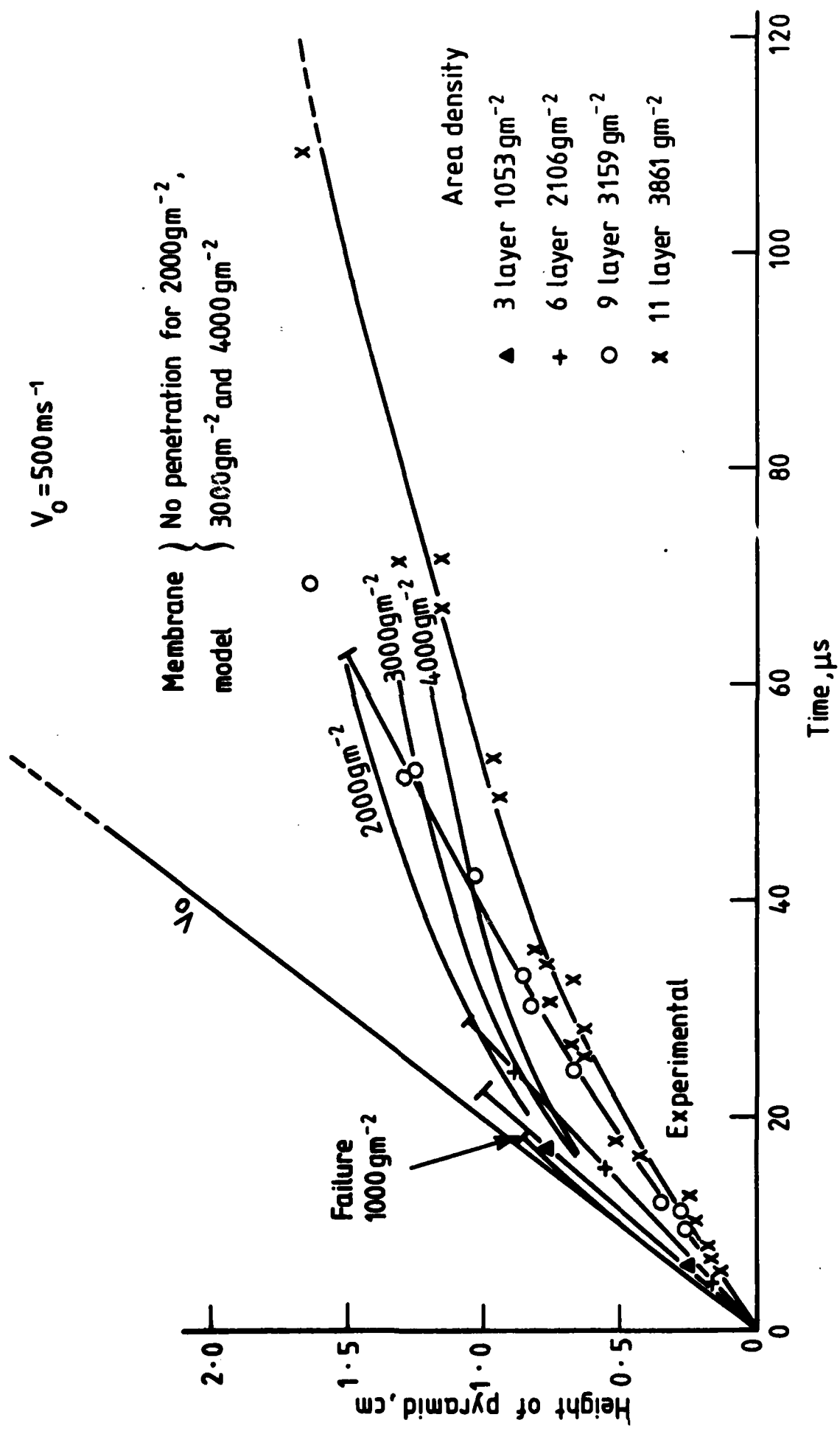
Pyramid height against time for multi-layered kevlar

Transverse wave displacement against time for multi-layered nylon   Fig.6(g)
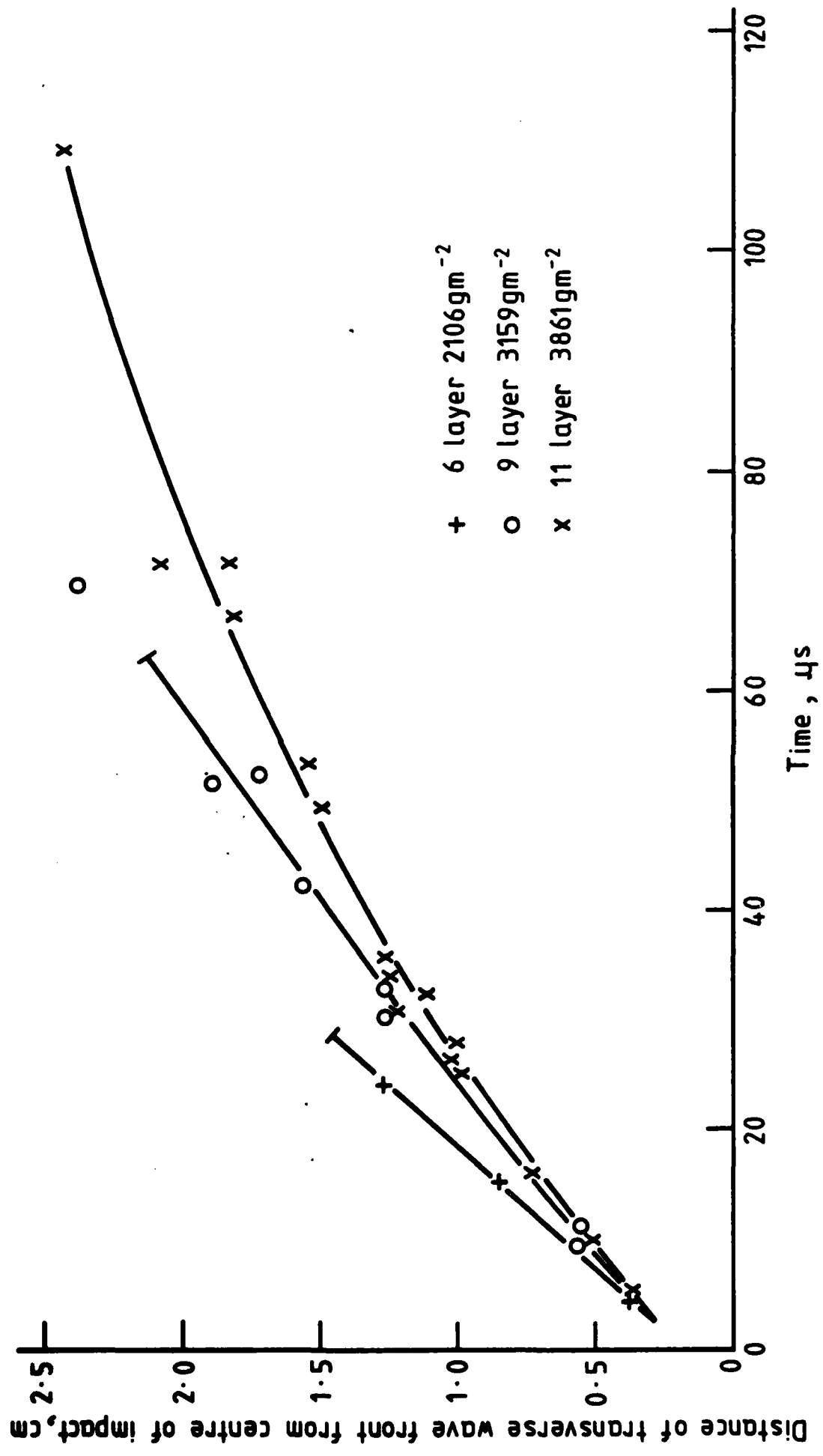
Area density

+ 8 layer $1928 gm^{-2}$

o 12 layer $2892 gm^{-2}$

x 17 layer $4097 gm^{-2}$

12 layer failure point

8 layer
failure point

Distance of transverse wave front from centre of impact, cm

Time, μs

Transverse wave displacement against time for multi-layered kevlar   Fig.6(h)

Time , μs

Distance of transverse wave front from centre of impact, cm

+   6 layer 2106gm^{-2}

o   9 layer 3159gm^{-2}

x   11 layer 3861gm^{-2}

56
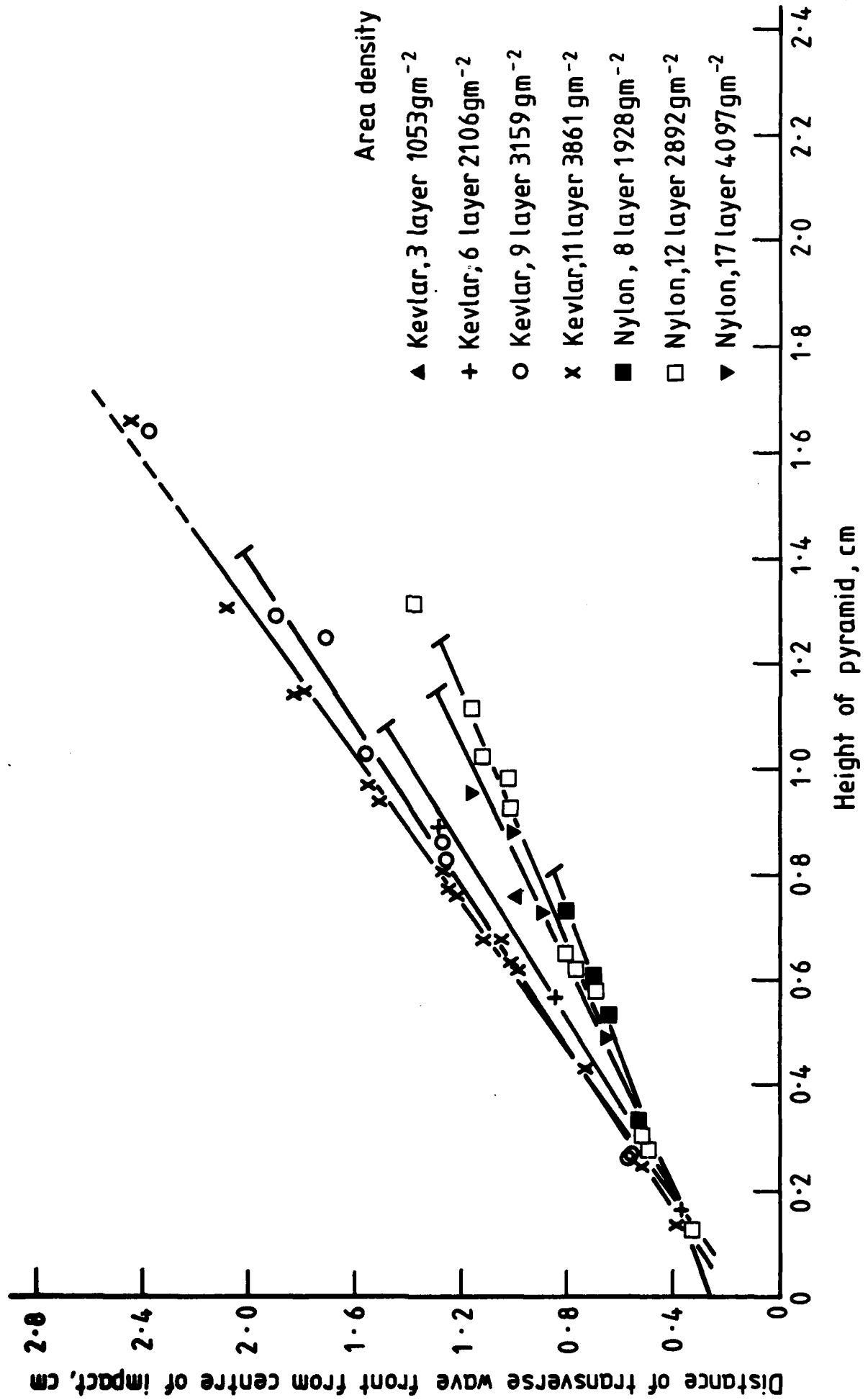
Transverse wave displacement against pyramid height   Fig.6(i)

Area density

▲ Kevlar, 3 layer 1053 gm^{-2}
+ Kevlar, 6 layer 2106 gm^{-2}
○ Kevlar, 9 layer 3159 gm^{-2}
× Kevlar, 11 layer 3861 gm^{-2}
■ Nylon, 8 layer 1928 gm^{-2}
□ Nylon, 12 layer 2892 gm^{-2}
▼ Nylon, 17 layer 4097 gm^{-2}

Height of pyramid, cm

Distance of transverse wave front from centre of impact, cm

REFERENCES

1   Mansell, J. 'Ballistic Impact of Woven Fabrics' Ph.D
thesis submitted to the University of Manchester
Institute of Science and Technology (1981).

2   Adeyefa, A. 'Mechanics of Single and Multi-layer
Synthetic Textiles Subjected to High Velocity Impact'
Ph.D thesis submitted to the University of Manchester
Institute of Science and Technology (1982).

3   Leech, C.M., Hearle, J.W.S., and Mansell, J.
'A Variational Model for the Arrest of Projectiles by
Woven Cloth and Nets' J.Text.Inst., Vol.70, Nov.1979,
pp.469-477.

4   Leech, C.M. and Adeyefa, A. 'Dynamics of Cloth
Subjected to Ballistic Impact Velocities' Computers and
Structures, Vol.15, No.4, 1982.

5   Cork, C.R. 'Aspects of Ballistic Impact onto Woven
Textile Fabrics' Ph.D thesis submitted to the
University of Manchester Institute of Science and
Technology (1983).

6   Maheux, C.R., Stewart, G.M., Petterson, D.R.,
Odell, F.A.
Dynamics of body armour materials under high speed
impact.   Part I. Army Chemical Centre, Maryland,
OCT, 1957.

7   Roylance, D., Wilde, W, Tocci, G., Ballistic Impact of
Textile Structures, Textile Research Journal, Jan 1973.

8   Morrison, C.E., Bowyer, W.H. Factors Affecting
Ballistic Impact Resistance of Kevlar 49 Reinforced
Composites, Fulmer Research Laboratories Ltd., Stoke
Poges, Slough, England, Contract No. A93B/189, (1980).

APPENDIX

Calculation of Kevlar strain so that the characteristics model would fail in order to give a resultant energy loss corresponding to that found experimentally.

Area Density $(g\ m^{-2})$	Energy Loss(J) (Experimental) ΔE	Projectile Energy at penetration (J) $125 - \Delta E$	Strain
500	20.1	105	>0.050
1000	36.9	88.1	*0.0375
1500	53.9	71.4	*0.031
2000	70.4	54.6	*0.26 ← highly uncertain large oscillations

* occurs after MAXIMUM OF STRAIN

The values for 1000 and 1500 fall close to those expected. This is reflected in figure 2d where the 1000 gm^{-2} and 1500 gm^{-2} results for the characteristics model do agree with the excperimental results.

Again now for nylon strain (see fig.2c)

Area Density	(ΔE)	$(125 - \Delta E)$	Strain
500 gm^{-2}	8.53	116.5	0.24
1000	17	108	0.205
1500	25.5	99.5	0.185
2000	34.0	91	0.170

Here experimental agrees with computational only at 500g m^{-2}. This is reflected in the above table where the breaking strain is 0.24. At higher area densities the model is grossly wrong.

The weakness of nylon could be due to either :

1. The melting of the yarns due to friction or to

2. The pushing aside of yarns by the projectile. Recent studies of damage to penetrated fabrics has shown that the number of broken yarns decreases as the projectile proceeds through the assembly.

e.g.   LAYER   No. of Weft yarns broken

LAYER	No. of Weft yarns broken
1	3
2	3
3	2
4	2
5	1
6	1
7	1

Projectile diameter =
        4.6 yarns

The effect of a yarn unloading from the projectile is as if
the yarn had broken at a lower strain.   This latter effect
could also explain the ballistic inferiority of Kevlar
compared to the Kevlar model, at high area densities (see
figure 2d).

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Nylon and Kevlar textiles are examined for their performance against impact by a 1gm projectile, when subject to impact velocities up to 200 m/s. The textiles are of varying areal density, and of varying layer composition and their performance is examined theoretically and experimentally. The theoretical models have been previously developed and are the characteristic model, membrane finite element and a multilayer finite element; the experimental /Cont'd.

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