

Impact perforation testing of stab resistant armour materials

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Abstract

This paper describes the development of a method for the investigation and comparison of materials for use in stab resistant body armour. A number of polymer composite panels of different thicknesses and construction have been tested. A dynamic test which simulated the real threat has been used and the results compared to a simpler quasi-static test that might be used in initial materials selection.

The materials tested were glass-epoxy, and glass-nylon composite panels of several thicknesses between 1.8 and 5.8mm. Additional tests were also performed on similar composites containing tungsten wires. An accelerated instrumented drop-tower was used to drive a knife through composite panels and record the force resisting penetration by the knife. The final penetration of the knife through the armour into a soft backing was also measured. For comparison, a similar geometry quasi-static test was carried out on the same specimens.

It was found that energy absorption took the form of an initial resistance to perforation and then by a resistance to further penetration. This is thought to stem from resistance to cutting of the panel material and gripping of the knife blade. The energy required to produce a given penetration in dynamic tests was found to be in good agreement with the penetration achieved at similar energies under quasi-static conditions. For the materials tested there was no significant difference between the penetration resistance of single or two layer systems. The penetration achieved through a panel of a given material was approximately proportional to the inverse square of the panel's thickness. The relative performance of different armour materials was assessed by plotting the energy required to penetrate a fixed distance against the areal density of the panel.

Introduction

There is a requirement to develop stab resistant body armour for use by police officers, as conventional textile ballistic armours provide little protection against stabbing attack. A considerable body of work exists on the impact response of composites, although this is largely divided into high energy ballistic impacts as reviewed by Savage (1), or relatively low energy blunt impacts (2). Obviously the wearer would prefer no penetration, however this might pose an unacceptable weight or thickness penalty. In order to make an

efficient knife armour it would be preferable to allow some (limited) penetration to occur, in which case energy would be absorbed by initial penetration and by subsequent passage of the knife through the perforation. No previous work exists on the mechanics of long slim projectiles penetrating composites at the velocities likely in knife attack, although perforation of composites by short projectiles has been widely studied. Zhu Goldsmith and Dhuran (3) studied Kevlar-polyester composite struck with conical and blunt ended projectiles at 200ms^{-1} . For blunt projectiles the main damage and energy absorption mechanism was delamination. However for conical projectiles energy absorption was due to fibre deformation and breakage. The conical projectiles were shown to penetrate the composite at less than a third of the velocity required for the blunt ended projectiles. Although some delamination did occur this was found to be only a minor effect.

It would therefore appear that increasing projectile sharpness lead to a transition from delamination failure to tensile or bending failure with less delamination. Fibres are forced out of the way of the projectile or fractured in cutting or bending. A knife impact might be expected to represent a stage beyond this, the slim profile of the knife would allow fibres in the plane of the knife to be forced out of the way with little deformation. Fibres across the plane of the knife would be cut, or fractured in bending. Very little data exists on the mechanisms of knife penetration or the performance of armour materials against such threats, and not until recently have test standards for stab resistant materials been proposed(4,5).

This paper will describe a quantitative impact test for the assessment of penetration resistant materials. Data from this test and from quasi-static tests will be shown for candidate composite armour systems.

Test Method

A diagnostic test has been developed which allows the force resisting knife penetration to be measured during the impact event. A Rosand IFW-8 accelerated instrumented drop-tower was used to propel a knife into test panels which were mounted against a plasticine flesh simulant block. The tests used a 105mm long, diamond section knife with an approximately straight taper (Figure 1). This shape was chosen in order to produce a relatively simple penetration/load response, as it is likely that both the magnitude and shape of the penetration/load curve will vary with knife shape. The knife was attached to a 5kg weight carriage and propelled into test materials with velocities between 3ms^{-1} and 5ms^{-1} calculated to give

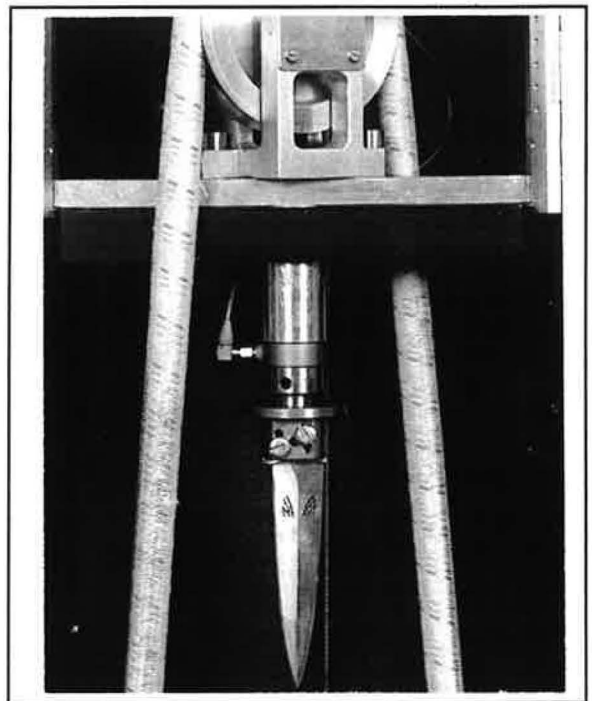


Figure 1 The weights carriage of the drop tower showing the knife blade and load cell arrangement.

kinetic energies at impact of 20, 30, 40, and 50 joules. A piezo-electric load cell mounted immediately behind the knife blade provided a measure of force during the penetration event. A sampling period of 149 μ s was used and a low pass filter was applied at 8.4 kHz. The velocity of the knife at the start of the impact event was measured by a pair of optical gates.

Panels of the test materials measuring 150mm x150mm were placed on a rigidly mounted open ended tube 110mm in diameter. The tube was packed with a ballistic flesh simulant to support the sample. The flesh simulant was in accordance with the specification given in NIJ standards (6). After each test this block was sectioned in order to measure the final penetration. All impacts were carried out along 0° or 90° directions.

For comparison, quasi-static tests were performed using the same test geometry but with loading velocities of 10mm/min. This used a conventional Instron universal testing machine which recorded the force/deflection response via a load cell between the crosshead and knife.

Materials

E-glass epoxy composites were fabricated by vacuum hot pressing of Fibredux 913-G-E-5-30 prepreg laminates. This unidirectional laminate has a resin content of 30% and a cured thickness of 0.125mm. This was layed up in $[0/90]_{ns}$ orientation with the number of laminates adjusted to give the correct thickness. Some panels contained a single $[0/90]$ array of tungsten wires situated centrally within the thickness of the composite. The wires were 100 micron diameter and spaced at intervals of approximately 3mm.

Nylon matrix composite panels were fabricated by a proprietary process in thicknesses from 2mm to 8.8mm using a $[0/90]_{ns}$ layup of unidirectional E-glass fibres. The fibres volume fraction was approximately 50%. Further panels were of a similar construction but also contained a single $[0/90]$ layer of tungsten wires approximately 1mm from each surface of the panel. The wires were of the same type as in the glass-epoxy composites but were at a 1mm spacing.

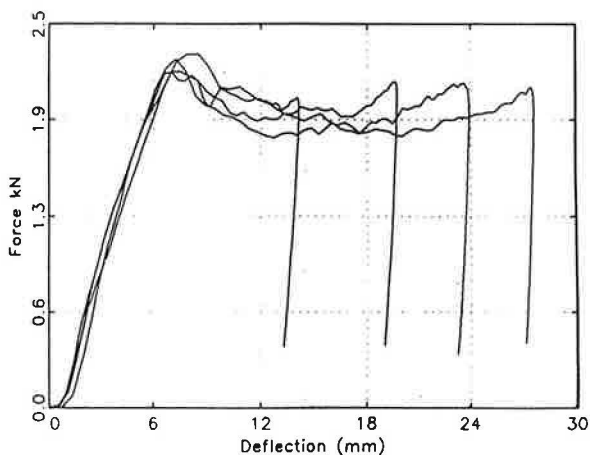


Figure 2 Force/deflection curves from the impact tests on 5.8mm glass/nylon composite at 20, 30 40 and 50 joule impacts.

Results

Force/time curves were obtained for each impact, from which force deflection curves were derived. In this case deflection was measured as the distance travelled by the knife after contact with the front surface of the test panel. Penetration of the blade was measured after each test, being taken as the distance from the rear face of the panel to the blade tip.

Deflection values were in agreement with measured penetrations taking into account the thickness of the test panel.

Figure 2 shows a typical force/deflection plot for the 5.8mm thick glass-nylon material over a range of impact energies. It can be seen that the start of the curve is similar irrespective of the impact energy but the latter portion extends further with increasing impact energy.

Figure 3 shows a similar set of force deflection curves for the 8.8mm thick glass-nylon panel. In this case only the 50 joule impact perforated the panel (by 2mm). The curves for non-perforating impacts show only a simple peak associated with deceleration of the knife as it penetrates the material. However once perforation occurs a second portion is added to the curve consisting of a steadily rising force with further penetration. Comparison of figures 2 and 3 show the different response to perforating and non-perforating impacts.

Similar sets of tests were performed on all the test panels and figure 4 shows the penetrations achieved as a function of impact energy for single tests.

Figure 5 shows the force/deflection curve recorded from the quasi-static test of the 5.8mm thick glass nylon panel. This can be compared to the curves in figure 2 from the dynamic tests. Table 1 shows the energy absorbed in the quasi-static tests at deflections equivalent to the final penetrations achieved in the impact tests. The data was produced by taking the actual penetration into the plasticine backing block

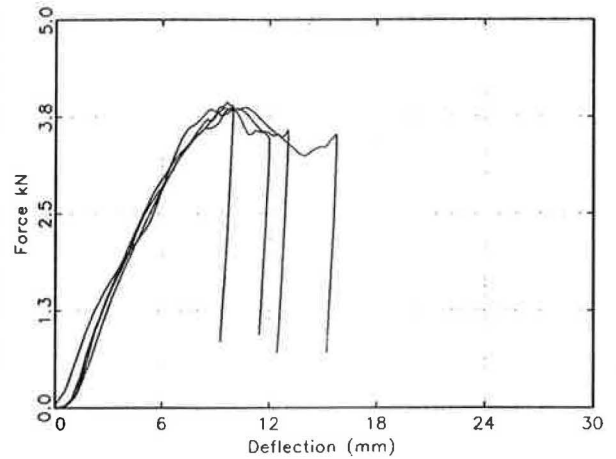


Figure 3 Force/deflection curves from the impact tests on 8.8mm glass/nylon composite at 20, 30, 40 and 50 joules.

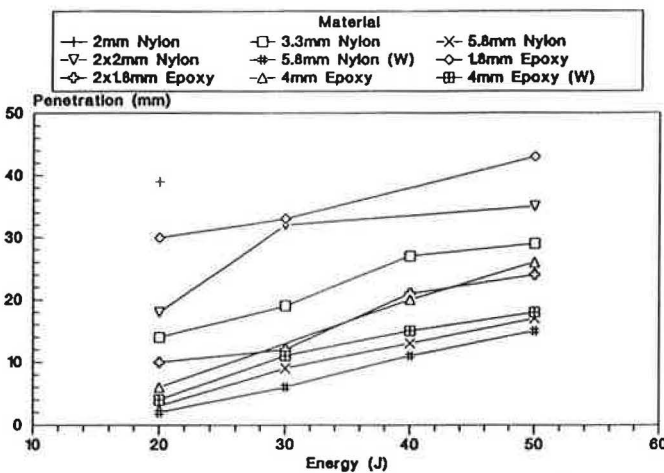


Figure 4 The knife penetration as a function of impact energy for the impact tests on various glass/nylon and glass/epoxy composites.

for a given input energy in the impact test. The energy needed to achieve the same penetration in the quasi-static test was then found by integration of the static force/deflection curve up to a that deflection. A correction was applied to take into account the thickness of the panel.

Discussion

The force/deflection curves in figures 2 show that there is an initial peak in the force at a deflection of 5-7mm during the perforation of the panel. Following this the knife slides through a steadily enlarging hole in the armour. The kinetic energy of the knife can therefore be absorbed by resistance to perforation of the armour and by providing resistance to further penetration after perforation.

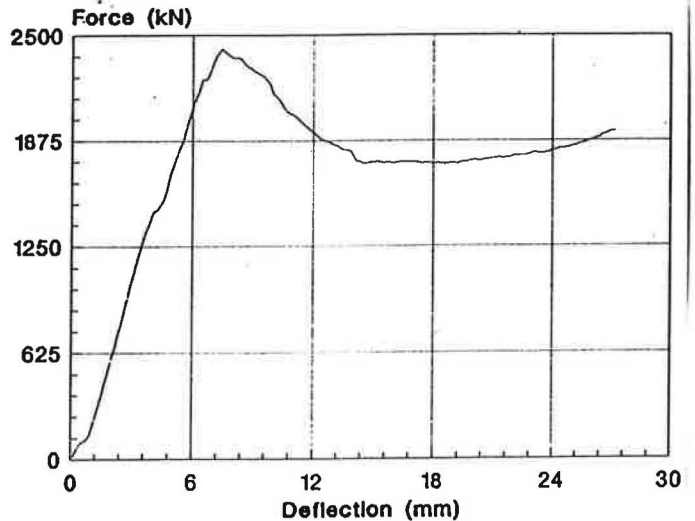


Figure 5 The force/deflection curve from a quasi-static penetration test on the 5.8mm glass/nylon composite. This should be compared to the impact data in figure 2.

In an effort to provide better perforation resistance in the armour, tungsten wires were incorporated into panels of both the glass-epoxy and glass-nylon composites. The force/deflection curves for the tungsten reinforced glass/nylon material is shown in figure 6. In both cases the penetration is significantly reduced by the presence of wires for only a small weight penalty.

Material	Impact energy Joules	Impact penetration Millimetres	Static energy at equivalent penetration Joules
2mm glass/nylon	20	45	14
3.3mm Glass/nylon	42	27	26
5.8mm Glass/nylon	45	16	46
5.8mm Glass/nylon/tungsten	41	11	45
1.8mm Glass/epoxy	20	30	16
4mm Glass/epoxy	40	20	43
4mm Glass/epoxy/tungsten	42	15	35

During the stage after perforation the force resisting penetration can come from two distinct mechanisms. As the knife penetrates the panel the hole through which it is passing has to be continually enlarged by cutting or fracture of the armour material. Friction between the knife and the panel caused by gripping of the blade within the hole will provide a second mechanism resisting further penetration.

Although resistance to cutting and hole enlargement is desirable, it is only present if the cross section of the blade is increasing. Very slim blades will experience little resistance to penetration once initial perforation has been achieved. The gripping mechanism is desirable as it provides a mechanism for absorbing energy from slim blades or relatively blunt ended non-tapering blades. A material

exhibiting this property would produce force deflection curves of the shape seen in figure 5 in which the force increases after initial penetration. Materials which provide less gripping of the blade or which have lower coefficients of friction in contact with the blade would exhibit force deflection responses similar to that figure 2 where the force is more constant after penetration.

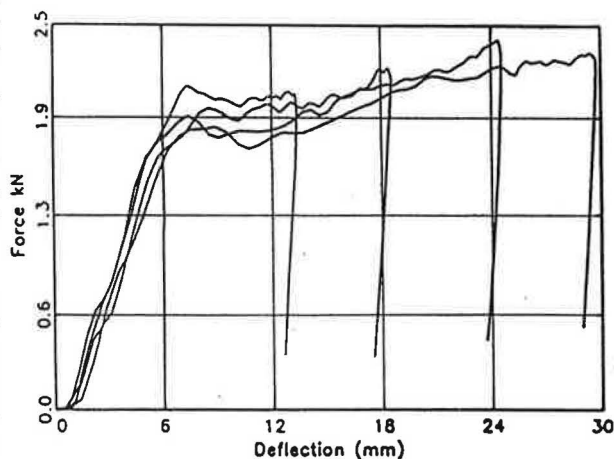


Figure 6 The force deflection curves from the impact tests at 20, 30, 40 and 50 joules, on 5.8mm glass/nylon composite containing tungsten wires.

A comparison of figures 2 with figure 4 shows that there is a generally good agreement between dynamic and quasi-static penetration tests. The energy for a given penetration given in table 1 shows a good agreement between the two types of tests for the thicker panels. For thinner panels the quasi-static tests shows significantly lower energies although a comparison is still possible. For panels that perform well a good assessment of dynamic performance can be made from quasi-static tests.

For a single material the penetration achieved for a given energy scales roughly with the inverse of the thickness although a better fit to the data is achieved if penetration is plotted against the inverse square of the panel thickness. In figure 6 the penetrations obtained in several thicknesses of glass nylon composite have been plotted against the inverse square of the panel thickness for each

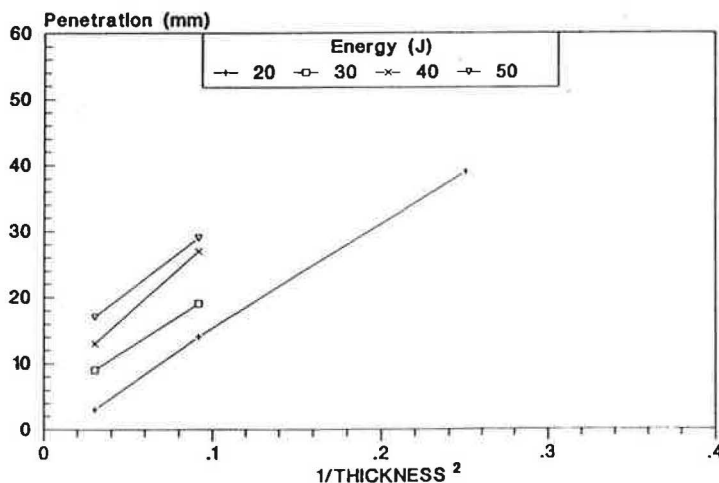


Figure 7 The penetration achieved through various thicknesses of glass/nylon composite plotted as a function of thickness⁻².

impact energy. It can be seen that for a given impact energy this plot is a straight line that passes close to the origin.

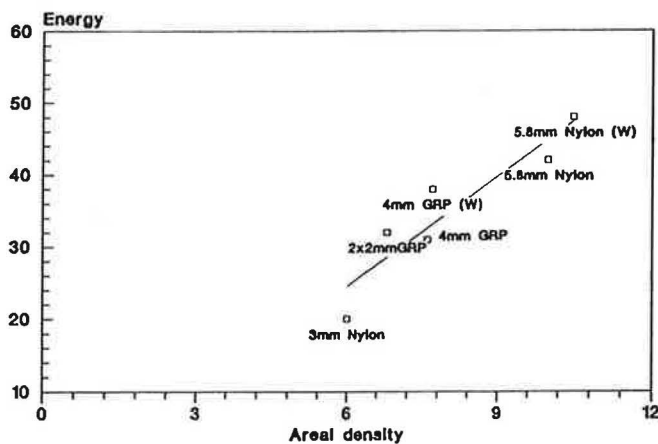


Figure 8 The energy required to penetrate 14mm through a panel plotted as a function of the areal density of the panel.

14mm has been chosen. For a set of values for one penetration better materials will lie to the upper-left whilst poorer materials will lie to the lower-right.

Comparison of glass-epoxy composites with nylon-epoxy composites shows little difference in efficiency. The performance of the composites scales approximately with weight. However the composites containing tungsten wires do perform significantly better than the standard composites of equivalent thickness.

For the glass/epoxy material the 2x1.8mm layers had a very similar performance to a single layer 4mm thick. For the glass/nylon composite 2x2mm layers had a performance which lay approximately midway between that of a single 3.3mm and a single 5.75mm panel. This would tend to indicate that for these materials there is no significant performance difference between a single thick panel and multiple thinner panels of the same total thickness.

Summary

The force acting on a knife during penetration of a material can be recorded during a dynamic impact test which simulates stabbing. Energy is absorbed during perforation and subsequent penetration of the target, the latter stage absorbing the majority of the energy when any significant penetration occurs.

There is good agreement between data obtained in quasi-static tests and that obtained from dynamic tests at up to 5ms^{-1} . Therefore for the materials studied it is possible to assess the stab resistance using only quasi-static tests.

The penetration achieved through a panel of a given material is proportional to the inverse square of the panels thickness.

A method is required to compare the performance of different armour materials or structures. It is likely that a performance standard for an armour would specify a maximum penetration for a given energy. In order to provide a comparison between materials of different thicknesses or densities the areal density (weight per unit area) can be plotted against the energy required to penetrate some arbitrary distance through the panel as shown in figure 7. The values are obtained by taking a horizontal line across figure 3 at a particular penetration and taking the intercept of this line with the plot for each of the materials. In this case a penetrations of

The relative performance of different armour materials can be assessed by plotting the energy required to penetrate a fixed distance against the areal density of the material.

There is no significant difference in performance between a single panel and two thin panels of equivalent thickness and weight.

Acknowledgement

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