The development of knife test blades for use in body armour stab resistant evaluation

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Abstract. Over the last 30 years there has been a development of the design features of test blades for use in body armour stab test rigs. In the early 90s the test methodology was relatively simple. Since then the design of test rigs and test blades has developed and continues to do so. This paper is a review of that development and the latest efforts in the Metropolitan Police Physical Protection Group to design a new knife to more accurately mimic the performance of real blades typical of those used in crime in the UK. This test blade was developed to investigate the stab resistance of not only body armour related materials but other fabrics used in operational uniform/clothing. The study summarises the work of identifying dimensional details of a large number of crime related knife samples, including measurement of cutting performance of both the tip and the edge, blade metallurgy and the estimation of impact loads derived from forensic analysis of stab incidents. The study is supported by computer modelling to gain further insight into the phenomena occurring in fabrics being stabbed. A new design of test knife has been developed and tested against a range of fabrics, polymers and metallic materials including those used in the construction of body armour. The paper gives details of the manufacturing process of the test blade and the method to sharpen the blade ready for use. One of the criticisms of some of the previous blades is that of cost. Details of how the design of the knife can achieve a cost reduction in the test process is included. This can justify a larger number of test strikes to assess the statistical variability of such a test.

1. INTRODUCTION

The design of body armour for police use is summarised in two main principles, firstly protection from the threat including knife, firearms and blunt impact attacks, and secondly the correct balance between protection and wearability must be achieved. In order to achieve such a balance, the test methodology must be as representative as possible. The design of the test knife is part of that consideration.

1.1 Review of Operational Incidents with Regard to Attack Method and Impact Dynamics.

A number of stabbing incidents involving body armour have demonstrated that the impact dynamics have been less severe than expected. In some cases, the areas of the body armour cover extending beyond the armour panel have been able to stop the knife. This has led us to research the feasibility of applying the best level of knife resistance to these areas, consistent with good wearability and heat dissipation.

1.2 Forensic Analysis of Operational Incidents

A number of forensic analyses have been undertaken in the last few years and it has been necessary to develop tests to assess the point sharpness and also the edge sharpness of knives. This work has led to a number of conclusions, namely the particular influence of both the sharpness of the point and the edge.

The point sharpness test is a quasi-static push of a specimen knife at 90° to a test material at a very low velocity while recording the resistive load. The skin/tissue simulant as used by Department of Engineering, University of Leicester is suitable [1].

Edge sharpness is the ability of the blade to cut whatever material it is designed to cut. So, a sharp razor will be different to a sharp felling axe. Sharpness of a knife can be estimated by measuring the cutting ability of paper. In PPG, a test rig has been developed to measure the load required on the blade under test to cut one layer of a defined paper sample. A simpler test is to use a knife to attempt to cut a sheet of A4 copier paper held by hand vertically. A commonly considered "sharp" edge knife will be able to cut the paper.

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1.3 Analysis of knives associated with crime

During the past 25 years the Metropolitan Police, Physical Protection Group (PPG) has carried out knife analyses of blades associated with crime. These knives include those used in attacks, seized during searches and handed in during amnesties. In all, PPG has undertaken 9 such analyses, the latest being in 2018 [2]. The categories of knives were; domestic knives, fixed blade (not domestic), folding knives, craft knives, butterfly and flick knives, machetes, cleavers/hatchets/axes, and miscellaneous. Of these categories, domestic knives have always been the highest proportion (except for 2008). This proportion has increased from 35% in 1995 to 73% in 2018. See Table 1.

Table 1. Knife analysis results (Percentages of the total number of incidents)

Type	Year								
	1995	1996	1997	2002	2004	2008	2013	2015	2018
Domestic knives	35	43.3	44.2	40.1	42	33.7	66.7	65	73
Fixed blade non-domestic	14	10.5	11	5.2	7.2	4.2	4.1	4.5	7
Folding knives	17	15.9	15.7	32.2	36.6	43.5	15.1	18.8	6
Craft knives	0	0	3.7	3.4	4.4	5.1	2.0	3.1	4
Butterfly & flick knives	15	4	12.5	6.7	2.3	1	0	0	1
Machetes	0	0	0	3.6	0	0	1.6	1.3	2
Cleavers, hatchets, axes	0	0	0	2.5	0.3	0.3	2.5	2.3	1
Miscellaneous	19	26.3	12.9	6.3	7.2	12.2	8.0	5	6

One significant observation from the inspection of domestic knives is that the condition of the point and edge was widely variable and the vast majority of them being dull or damaged to an extent where they were poor in cutting performance. For examples see Figure 1.

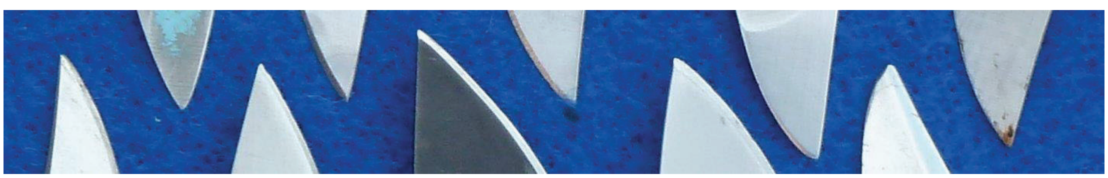

Figure 1. Examples of knife points.

1.4 Results of Geometry, Tip and Edge Sharpness Inspection

A second observation from the inspection was the range of typical knife blade shapes. The tip angle of the blade, tangential to any curved surface, was measured and the population distribution calculated. The average angle was found to be 45°. The included flank angle of the blade was measured, the typical angle was found to be 20°. The sharpened edge angle was found to be 30°. See Figure 3.

1.5 Theory of Penetration of Stab Resistant Body Armour

Body armour stab resistant materials are generally thin homogeneous layers (plastics or metals), chain-mail, or woven aramids (plain or with resination).

The theory of penetration of homogeneous materials comes from the study of metals. There is general agreement that the work done in producing a knife type perforation in metal is divided into 3 specific characteristics;

- firstly, the fracture of the material in front of the sharp edge to overcome the molecular binding forces

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- secondly, deformation work near the fracture crack and further away from the area which will include elastic and plastic deformation, and
- thirdly, frictional force resisting the perforating knife; a result of material properties and surface finish [3]

For the typical body armour materials, the proportional contribution to the energy dissipation by each of these cutting characteristics will vary. For example, armour designs with metal platelets may typically offer 35% fracture, 25% deformation and 40% friction resistance. Multi-layer aramid panels may offer less frictional resistance. Polymers like polycarbonate in thin platelets will offer a particularly high level of fracture and friction resistance. Chainmail with aramid layers will present a complicated balance of fracture, deformation and friction resistance [3].

1.6 Mechanical Properties of Knives

Knife blades are made from tool steels, carbon steels, and stainless steels. Hardness is required to maintain a sharp edge, but brittleness will lead to blade fracture. However, the blade edge has to be sharpenable; excessive hardness makes this difficult. Toughness, to allow strength without fracture, is very important. Finally, corrosion resistance is essential, particularly for domestic knives, the largest category of blades. A very popular material for knife manufacture is the 400 series stainless steel. Typical mechanical properties for 440C stainless steel heat treated knife blades are: Tensile Strength 2030 MPa; hardness 59 HRC; and impact Charpy 9. It has a high chromium content and therefore a high corrosion resistance, and is able to be easily sharpened.

1.7 The History of Assessment Methods and Test Blades

Table 2. History of test blades since 1990

<table>
<tr><td></td><td colspan="2"></td></tr>
<tr><td>Swiss-German dagger blade
UK PSDB No 5 blade
UK PSDB No 1 blade</td><td>MPS Triangular blade
CEN blade
UK HOSDB P1B blade
MPS new blades</td><td>Shown left to right</td></tr>
</table>

1.7.1 Swiss German (1992) [4]

The test rig in the Swiss/German stab test was a vertical drop tower. The double edged test blade was held in a circular sabot, of mass 2.6 kg, to give impact energy of 35 J and a maximum limit of 20 mm perforation was allowed.

1.7.2 Home Office UK (1993) [5]

The original blade research undertaken by UK Police Scientific Branch (PSDB) for the Home Office (HO) stab test selected 2 commercial sheath knife blades (No 1 and No 5) which were fitted into sabots and fired horizontally at 42 J into a vertically mounted target assembly, with the body armour sample backed with a Plastilina block.

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1.7.3 Metropolitan Police (1995)

In the Metropolitan Police (MPS), in 1995, after a series of police officer fatalities from stab attacks, a feasibility study to provide body armour was launched. Body armour samples made to meet the HO 42 J test were not sufficiently wearable for general use, so a development of a new test method was undertaken. Some armour samples were made of platelets (which would pass the 42 J test at 90° impacts but fail at impacts at acute angles). To test at various angles, a swinging arm test rig was introduced. The test blade used was a tapered triangular section engineered blade. A pass/fail criterion of 20 mm maximum perforation at 25 J energy was required.

1.7.4 CEN draft standard (2000)

The CEN Body Armour committee agreed on an engineered blade that would provide a more consistent performance than the test blades which had been in use in the recent years. One difficulty with engineered blades was the problem of weak tips as a result of the need for a grinding process limited to flat surfaces in order to reduce manufacturing costs. The interesting design feature to overcome this was an additional chisel point on the extreme tip to strengthen the point. The design concept was to produce a blade that was one use only and of only 1-2 Euros in price. The CEN methodology involved a vertical drop tower design. The CEN Body Armour Standard was never ratified.

1.7.5 PSDB 2003 Body Armour Standard [6]

The 2003 HO Standard review adopted a vertical drop tower and sabot with an internal damper and a backing material assembly of elastomeric plastic foam layers. The HO Body Armour Standard review in 2003 adopted a new design of engineered blade that was designed to replicate the stabbing performance of the No 1 blade. The product was named the P1B blade.

1.7.6 VPAM Body Armour Standard [7]

In 2004 the VPAM, Test Standard "Stab and Impact Resistance" was introduced and used across mainland Europe. The VPAM used a drop tower, the P1B blade and a backing of Plastilin der Fa. Carl Weible.

1.7.7 Metropolitan Police (2005)

The Metropolitan Police also reviewed their test regime to a drop tower design. However, the damped sabot was removed to improve consistency in the results. The P1B blade was used in these tests.

1.7.8 Metropolitan Police Quality Assurance (QA) test (2008)

In 2008 the Metropolitan Police designed a specific stab test rig to further improve the consistency of results because the previous test methods were not sensitive enough to be used as a QA tool for production. The result was a drop tower design with the blade separated from the sabot, the backing arrangement consists of an anvil to allow the armour to deform, an aperture through which the test blade could perforate and a camera to observe the perforating test blade tip from below. The rig yielded more consistent results and has been used for this purpose since. The P1B blade was used in this test setup.

1.7.9 Home Office, Body Armour Standards HOSDB (2007) [8] and CAST (2017) [9]

The current UK HO Body Armour Standard was issued in 2017. Much of the methodology is similar in principle to the previous issue. The P1B blade is used.

1.8 Lessons from history

From the PPG analysis of knife blades, armour perforation tests, the history of previous test methods and forensic research, we have come to the conclusion that a new design of test knife is necessary. See ref [10].

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2. DESIGN FEATURES OF THE NEW BLADE

It is important that the test blade is representative of real blades that may be used in stab related attacks, The geometry of a large number of typical knives was studied and the most common design had a tip angle of 45° at the point and included flank angle of 20° and sharpened edge angle of 30° (see Figure 3). This test blade was developed to investigate the stab resistance of not only body armour panels but other fabrics used in body armour covers and operational uniform/clothing, including:

- A multi-layer resinated anti-stab material panel
- A chainmail and aramid based armour panel
- Thin metal sheet
- Fabrics typically used in body armour covers

2.1 The Manufacturing Process of the Test Blade and Method to Sharpen the Blade Ready for Use.

The material selected for the new blade is AISI type – 01 ground flat stock and is available in lengths of 15 x 2 mm rectangular section. It can easily machined and ground to shape. When hardened and tempered, it can be brought to 62 HRC which is harder than normal knives so the test knife edge will be maintained in use and it can be re-sharpened for future use. It is not as corrosion resistant as ordinary blades, but this is not a disadvantage for a test blade as it is used only in a laboratory.

The shape of the test blade is based on three main dimensions: a tip angle of 45°; a curved sharp edge; a maximum width of 25 mm; and a flank angle of 20° with a sharpened edge angle of 30°.

There are two options for the Metropolitan Police Service (MPS) test blade, one for use in the HO test rig with a 15 x 2 mm shank to fit the sabot, and a 25 mm wide blade (MPS45/80/25). The second option is a parallel sided shank with the same geometry at the impact end but with a reduced width of 15 mm; designed to be used in the MPS QA test rig. This option is necessary because the MPS QA test rig is limited to blades only 15 mm wide (MPS45/80/15). Each has a curved edge radius of 80 mm. They perform identically up to a perforation depth of about 20 mm.

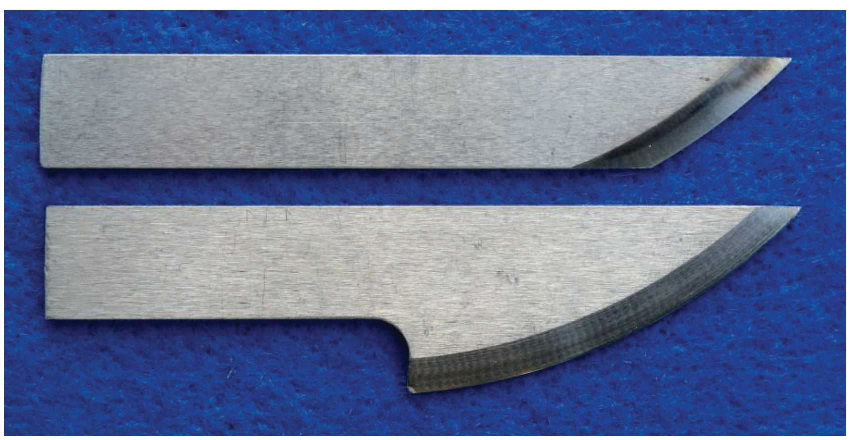

Figure 2. The MPS45/80/15 and MPS45/80/25 test blades (approximately actual size)

One of the criticisms of some of the previous blades is that of cost. The price from suppliers has generally been higher than anticipated, as the practice of single use has made the process of knife testing expensive. The new knife is designed to be sharpened by hand and be able to be used repeatedly. The re-sharpening process involves use of a ceramic whetstone. The sharp edge has an included angle of 30°. It is important to note that any burrs should be removed by stropping and then a simple inspection under magnification to check any burr has been removed. To assess the sharpness of a blade in the test laboratory, a simple test can be performed: the blade is ready for use when it is visually burr free and able to cut one layer of 80 g/m^2 paper held vertically.

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2.2 To Verify the Blade and Compare with the Standard P1B

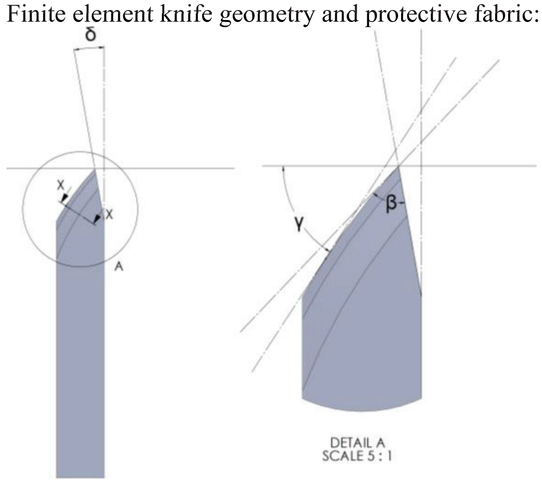
A comparison trial was undertaken to estimate the perforation with energy characteristics. Using the MPS QA test rig, each blade was used at a range of energy levels up to the point of complete perforation. Owing to the difference in shape between the P1B and the MET blade, for a given perforation depth, the cut width is approximately double with the MET blade. Three different types of armour panel construction were used:

- Resinated aramid: The perforation of the MET blade was similar to the P1B over the whole range of energies up to approximately KR1 level.
- Chainmail and soft aramid quilted pack: The perforation of the MET blade was less than the P1B up to about the energy level of the minimum level of stab protection (KR1) required by the UK HOSDB test level, then the MET blade perforated deeper up to complete perforation with higher energy levels.
- Mild steel 0.5 mm: The perforation of the P1B blade was about double up to the point of complete perforation. (This meant that the crack width formed by each blade were similar)

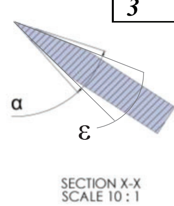
3. KNIFE GEOMETRY COMPARISON ANALYSIS USING FINITE ELEMENT ANALYSIS

With an aim to identify the effect of blade geometry on cutting ability, finite element (FE) models were created of varying test knife designs. These include a standard test knife (knife 1), a sharpened test knife (knife 3), and a sharpened knife (knife 2) with blunt second edge. Finite element modelling is particularly suited to this analysis style as it is fully repeatable, in addition to providing in-depth results, including local stress/strain levels, without the material itself being deformed during sample extraction from the rig for inspection. Furthermore, material movement can be studied in depth using software, thus not requiring modification of the physical test scenario to enable high speed photographic video recording.

Finite element knife geometry and protective fabric:



Knife	**Cutting face Angle [°] (α)**	**Blunt Face Angle [°] (δ)**
1	2 x θ	0
2	θ	10.56
3	θ	0



Angle	**Definition**
α	Sharpened Edge Angle
β	Tip Angle
γ	Cutting Edge Angle
δ	Blunt Face Angle
ε	Flank Angle

Figure 3. Geometry of blades and angle identification

The material consists of 2 layers of plain weave aramid, with a tow width of 0.83 mm, a tow thickness of 0.155 mm, and a tow gap of 0.10 mm.

3.1 Modelling Strategy

The model was created to simulate the physical test scenario, carried out with the MPS QA test rig. In order to allow timely completion of the simulation, the model was simplified in terms of: the knife was modelled as rigid (undeformable); material proximal to the tip impact area was modelled as having 5 fibre bundles per tow; material distal to the tip impact area was modelled as 2D (shell) elements; there is no

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cross-fibre connectivity at the area proximal to the tip impact; the knife impacting the fabric was loaded with a mass of 0.05 kg, travelling at 3.706 m/s.

The material was first simulated draping over the target disc. The output showing the draped material was then utilised as the input geometry for FE knife impact testing, removing any artificial gap between the material and the disc. The material was trimmed post-drape so that the sample did not overhang the outer perimeter of the target disc. The simulations were run until the impacting knife reached a vertical velocity of 0 m/s.

3.2 Results Overview

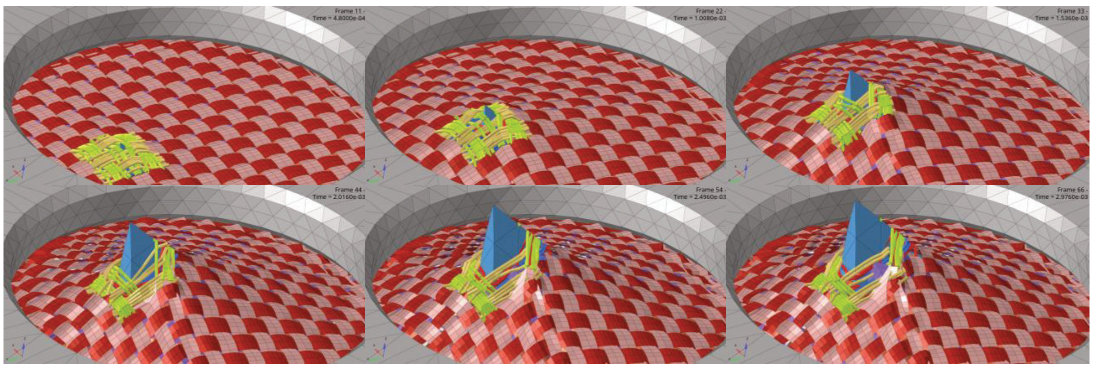

Figure 4. Images of simulated material deformation during knife tip impact.

When observing the material behaviour, three main stages can be observed: 1 – initial puncturing of the material and gathering around blade; 2 – cutting and slippage of fibres causing material relaxation around puncture location; 3 – tightening of material around blade. The differences in these three areas will determine the penetration of the blade into the material. During stage 1 of the impact the material tow is penetrated by the blade, causing fibres to pass over both sides of the blade, in addition to separating to span both the sharpened and blunt faces. This can be seen in Figure 5.

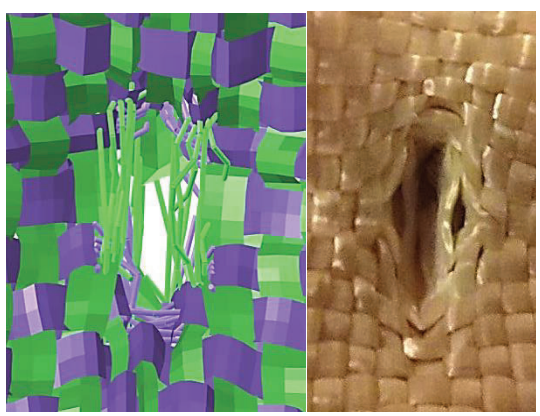

Figure 5. Comparison of physical and finite element model deformation.

Comparing the finite element results to comparable drop tests conducted – the material is shown to behave in a similar pattern, with 4 tows being severely deformed. Fibres travelling parallel to the knife body (horizontally in Figure 5) were deformed less than those travelling perpendicular to the knife face (vertically in Figure 5).

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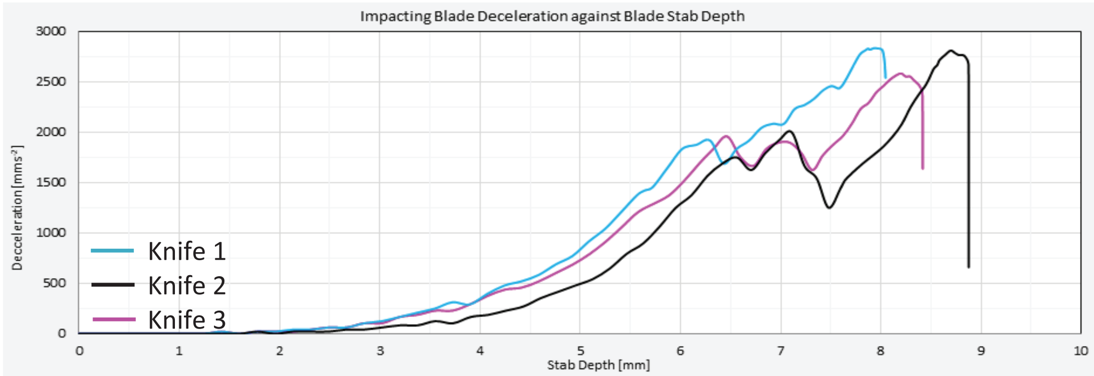

Figure 6. Simulated blade deceleration against blade stab depth.

3.3 Analysis of Results

Figure 7. Comparison of deformation for knife 1 (grey) and knife 3 (purple), created by overlaying results from two tests.

It can be seen from Figure 6 that blade 2 penetrated the material by the furthest distance (8.88 mm). Blade 1 penetrated the material by the shortest distance (8.05 mm), travelling a shorter distance than knife 2 and 3 (8.42mm). The behaviour of the blade can be seen to follow the three stage process described previously, with the first section, puncturing and gathering of material occurring before 6mm. The second stage, slippage and cutting of fibres, occurs between 6mm and 7-7.5 mm. The final stage, material tightening, occurs after 7-7.5 mm.

Knife 1, due to its blunt cutting face, does not penetrate the material as far as knife 3 (Figure 6). It can be seen that the vertical fibres in Figure 7 are required to undergo further deformation in order to accommodate the thicker cross section of knife 1. This tightens the fibres travelling horizontally against the cutting and blunt edges of the knife, thus requiring more force for the knife to pass into the material.

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3.4 Observations and Conclusion

Knife 2 penetrates the material further than knife 3. This was found to be caused by the gradient of the cutting edge at the blade's proximal tip; due to the top section of the knife being removed to accommodate the angled blunt face, the gradient of the cutting edge to vertical is reduced from 45° to 35°. The total tip, including blunt face angle, remained at an approximately constant angle of 45°.

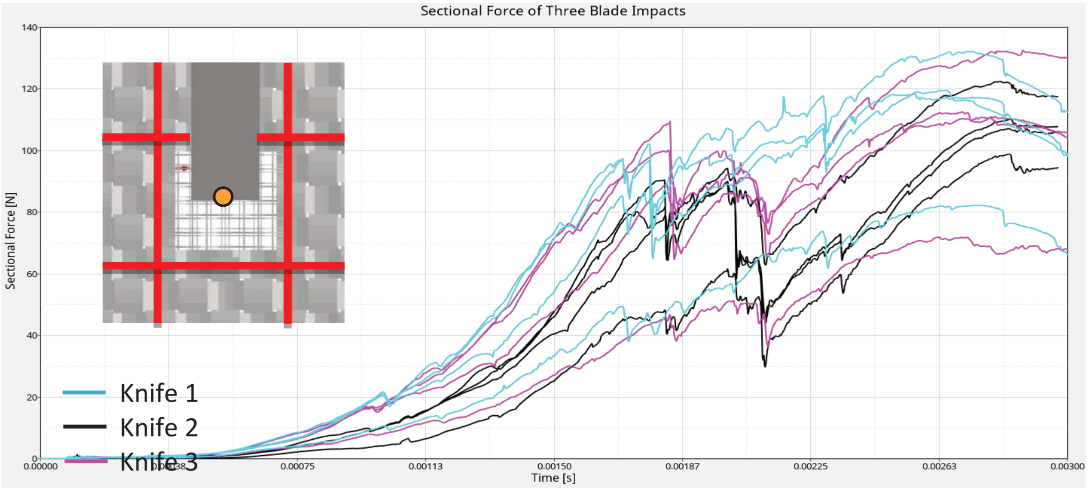

Figure 8. Sectional force (total axial forces measured in a single cross-sectional cut across all fibres) for blade tests; pictorial representation of sections (red) in relation to knife impact area (orange)

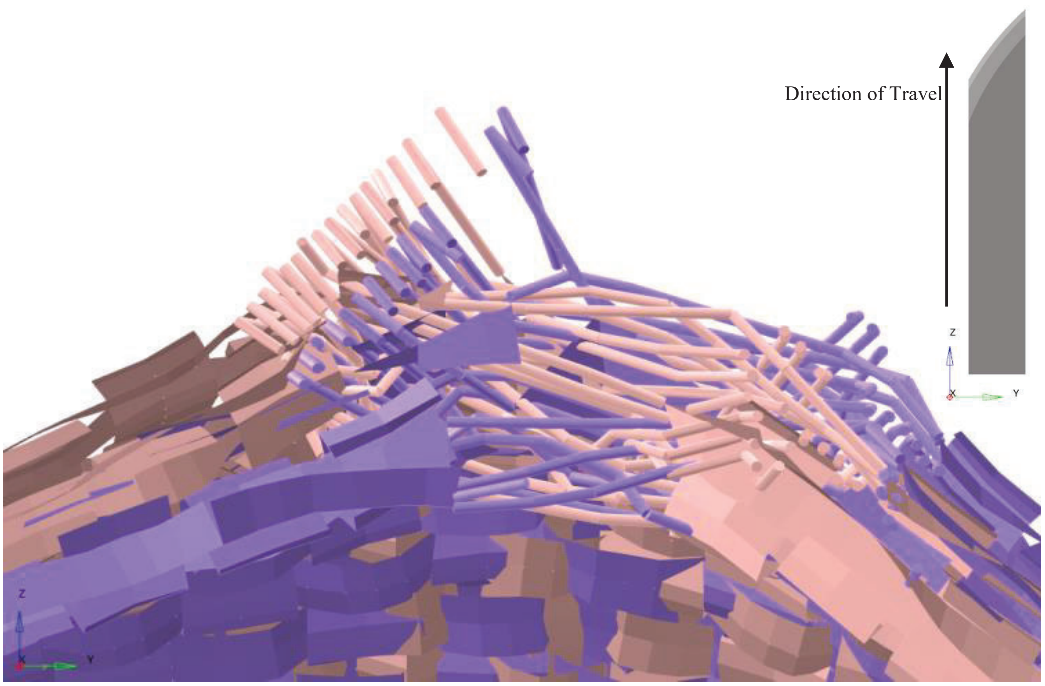

Figure 9. Comparison of material cross-section deformation for knife 2 (purple) and knife 3 (pink), knives omitted for clarity

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The difference in cutting edge angle is clearly displayed in Figure 9. The cutting edge is steeper for fibres impacted by blade 2, causing them to slip further down the cutting edge, thus undergoing lower levels of tension, as they are draped over the cutting edge more loosely. This is reflected in the sectional forces within the material (Figure 8). It is clear to see that blade 2 has consistently lower sectional forces than blade 3, with the exception of the lowest trace, produced by fibres positioned horizontally across the vertical blunt face. The sum of the sectional forces is lowest for blade 2.

The total number of 1D elements ruptured (indicating failure of several fibres) is 1 for both knife 1 and 3, compared with 2 for knife 2. This is likely due to the increased tension in the fibres on the blunt edge of the blade, causing more force acting perpendicular to the tow.

3.5 Analysis Conclusion and Connection to Knife Impact Testing

The FEA modelling conducted in this section highlights the difference in stab depth when blade geometry is altered. Decreasing the cutting face angle allows the blade to penetrate further into the woven material, when loaded with a set energy, this suggests that the smaller included angle of the MET knife allows better cutting of the material. Increasing the cutting edge angle, as seen in blade 2, increases the penetration observed in the material, this is reflective of the P1B knife performance. The increased cutting depth gained by including an angled blunt face outweigh the disadvantage of having a larger cross sectional area for the tip region.

It has been observed in the finite element models that the gathering of material, and the distance of fibre spread around the puncture location, demonstrate the complexity of material failure; thus suggesting further work is required on the subject of material behaviour during blade impacts.

4. CONCLUSIONS

Over a long period of time, the Physical Protection Group has believed that an improved blade is necessary. A large amount of body armour testing and research into armour scheme designs and a number of forensic analyses of stabbing incidents have been the motivation behind this project. The blade presented here will be used by the PPG in future. The MET blade has a greater cutting performance than the P1B forming a wider cut for a given perforation depth. The P1B blade has a greater piercing action than the MET blade. The MET blade is a more representative blade and so will be adopted in MPS body armour testing alongside the P1B.

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