Edge Performance of Ballistic Helmets

P.M. Fenne and P.L. Gotts

[1]*Physical Protection Group, Metropolitan Police Service, 60 Albany Street, London NW1 4EE*
paul.m.fenne@met.police.uk
[2]*Phil Gotts Consulting Ltd, 23 Thorney Road, Capel St Mary, Ipswich, Suffolk IP9 2HL, UK*

Abstract. Within Police Forces there is now a trend to specify high-cut ballistic helmets for reasons of ergonomics, mass and compatibility. This of course reduces the protective area of coverage compared to a standard-cut helmet. With reduced area of coverage, it is more critical than ever that as much of the area of the helmet as possible provides ballistic resistance. This means that it is critical to assess the performance of the helmet close to the edge of the helmet, and ultimately determine how close to the edge a shot can be defeated. There appears to be little history of edge testing of helmets, and even though an edge test was incorporated into VPAM HVN 2009, there seems to be no background evidence as to why the particular limit was chosen. To this end the Metropolitan Police Service (MPS) Physical Protection Group (PPG), and Phil Gotts Consulting Ltd (PGC), have conducted a programme to support the writing of a test method for edge testing of helmets in general, and high-cut helmets in particular. The work has been to research the effects of ballistic impacts at progressively reduced distances from the edge. The test results were analysed to understand the impact mechanisms involved. Behaviour of filaments and the effects of varying adhesive forces within the matrix were identified. Generic samples of both para-aramid and ultra-high molecular weight polyethylene (UHMWPE) were used, as they are known to behave differently. The research identifies the exact point of impact along with any bullet deflection as a result of firing close to the edge and provides both permanent and transient back-face deformation information. The impact event was recorded using high-speed video. The content of the work is relevant for compiling a test methodology and has potential with respect to the design of helmets to improve ballistic protection along the edge of helmets.

1. INTRODUCTION

Within Police Forces there is now a trend to specify high-cut ballistic helmets for reasons of ergonomics, mass and compatibility. This of course reduces the protective area of coverage compared to a standard-cut helmet. With reduced area of coverage, it is more critical than ever that as much of the area of the helmet as possible provides ballistic resistance. This means that it is critical to assess the performance of the helmet close to the edge of the helmet, and ultimately determine how close to the edge a shot can be defeated. If a ballistic helmet cannot defeat a low velocity bullet relatively close to the edge, then its effective area of coverage is reduced, burdening the wearer with added weight and discomfort for no added protection.

Figure 1 shows the different geometries of generic standard, mid and high-cut helmet designs, showing the reduction in area of coverage with the high-cut helmets.

Figure 1. Standard-Cut (left), Mid-Cut (centre) and High-Cut (right)

In order to assess the ballistic edge performance, ballistic testing needs to be conducted, which is easier to do if there is a suitable test method to use. Currently only one test standard includes edge shots on ballistic helmets, which is VPAM HVN 2009 [1]. This study aims to develop a test method and not to assess the performance of specific ballistic helmets.

2. VPAM HVN 2009 (2017)

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There appears to be little history of edge testing of helmets. A literature search conducted in early 2022 identified only a single test standard which incorporated an edge test – VPAM HVN 2009.

The VPAM (Vereinigung der Prüfstellen für angriffshemmende Materialien und Konstruktionen) organisation is an association of German-speaking test organisations, who have produced their own series of test standards and methods. VPAM HVN 2009 is a standard which specifies the test methods used for helmets (H), visors (V) and neck-guards (N). Focussing upon the helmet (H) part only, there are separate ballistic perforation-resistance and behind helmet blunt trauma parts of the testing.

As there are no threat levels included within HVN 2009, it calls upon another VPAM standard, APR 2006 [2], which in theory allows any of 14 different levels to be chosen. A number of these levels are completely irrelevant for helmets, and even pushing the boundaries of current technology, only levels 2 to 7 are likely to be specified.

The shot pattern specified for the helmet consists of 5 impacts around the helmet, 80 mm from an edge or another shot. The VPAM then states that a further shot is to be placed at 20 + 5 mm (i.e. between 20 and 25 mm from the edge) from an edge. Questioning of the current VPAM committee has not been able to acquire any evidence of why the edge shot, at that particular distance from the edge, was included for the first time, in the 2009 version of the standard. It was not part of the 2005 version, which many of the VPAM test laboratories seem to still be using.

During the development of the MPS edge test method, a single helmet specified to VPAM HVN 2009 was tested. The results in Table 1 show that the design of that particular helmet does easily meet the 20 + 5 mm edge test requirement.

Table 1. Ballistic Test Results for VPAM HVN 2009 Helmet

Shot No	***Impact Point***	***Velocity (m/s)***	***Outcome (N/P)***	***Comments***
1	Crown (front)	404	N	
2	Crown (rear)	405	N	
3	25 mm from rear edge	404	N	
4	20 mm from rear edge	415	N	
5	10 mm from front edge	415	P	jacket impact on witness
6	15 mm from front edge	413	N	
7	15 mm from side edge	408	N	
8	15 mm from side edge	415	N	

3. DEVELOPMENT OF TEST METHOD

To this end the Metropolitan Police Service (MPS) Physical Protection Group (PPG), and Phil Gotts Consulting Ltd (PGC), have conducted a programme to support the writing of a test method for edge testing of helmets in general, and high-cut helmets in particular.

The initial series of trials used the helmet mounted in its usual orientation, as shown in figure 2. It soon became obvious that this was not ideal, as it was difficult to determine whether it was a perforation (P) or non-perforation (N) after each shot, and there was a general feeling that the detail of what had actually happened during the event was something of an unknown. There was also the tendency for bullets which were a non-perforation to drop out of the helmet, either at the time of the impact, or during subsequent shots, or handling of the helmet.

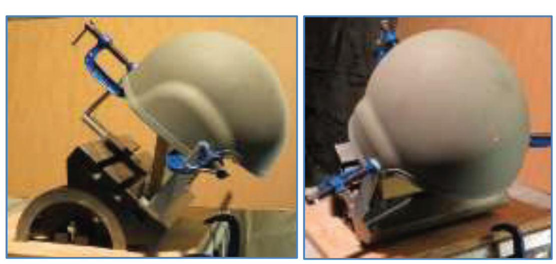

Figure 2. Helmet mounted to Test Rig in Typical Orientation

The obvious solution for the following round of testing was to invert the helmet. In fact, at the end of this particular trial this was attempted with the current rig and one of the previously tested helmets. This inversion added several advantages:

- Any non-perforation result bullets are retained in the helmet shell
- It is simple to see what the edge of the helmet looks like without removing it each time
- It allows for further instrumentation to be included easily.

The inversion of the helmet has allowed further development of the test method to include the use of high-speed cameras, which has greatly increased the ability to understand what is happening during the bullet / helmet interaction. This allows the trajectory of the bullet to be observed, and aids with the determination of whether a shot should be considered as a perforation or non-perforation. This also allows an estimate to be made of the temporary deformation of the helmet shell, as well as the permanent deformation.

The increased ability to visualise the impact event has also led to other issues which need to be considered. For example, when a bullet impacts an edge, what should be considered as a perforation or non-perforation. Previously with helmet ballistic testing, this has been determined by a witness placed within the helmet, but this may provide a false impression, due to the potentially erratic trajectories of some bullets post-perforation, as well as the possibility of bullet break up with parts taking different trajectories.

4. EDGE TESTING OF HIGH-CUT BALLISTIC HELMETS

A series of three trials were conducted using low-cost high-cut ballistic helmets procured from China. These were manufactured from either para-aramid or ultra-high molecular weight polyethylene (UHMWPE) and specified to meet NIJ-0101.04 Level IIIa. The designs were identical for both materials, with the para-aramid shells being approximately 5 % heavier than the UHMWPE ones, whereas the UHMWPE helmet shells are approximately 25 % thicker than the para-aramid ones. Surprisingly, perhaps, the para-aramid helmets were also the more expensive items. For the trials the para-aramid helmets are identified as 'PA' followed by a number relating to the trial series part, while the UHMWPE helmets are identified with 'PE' followed by the appropriate number.

All trials were conducted with the same ammunition – DAG 9 x 19 mm DM11A1B2 FMJ (full metal jacket), fired as full-charge, out-of-the-box ammunition, at 405 ± 15 m/s from an appropriate proof barrel. The bullet's impact velocity was measured using optical sky-screens. The outcome of each shot was deemed to be either a perforation (P) or a non-perforation (N). The trial configuration was changed slightly across the three trials, but the changes were minimal and only affected the ease of mounting the helmet shells on the rig. The general configuration is as shown in Figure 3.

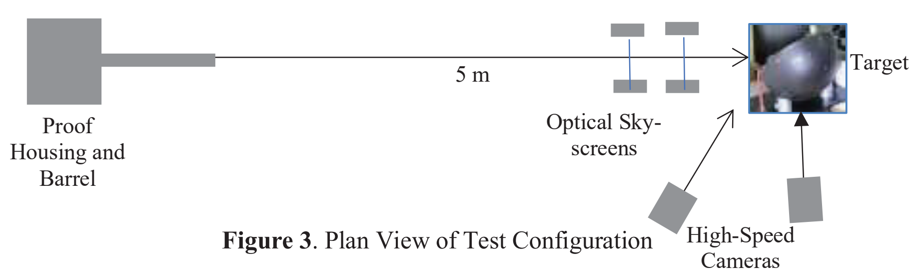

Figure 3. Plan View of Test Configuration

Figure 4 shows the helmet mounted on the rig in its inverted position. The 45 º mirror allows one of the high-speed cameras to look down into the helmet, while the other high-speed camera shows the view of the bullet impacting the helmet and hence confirms the orientation of the bullet impact to the surface. This high-speed video view also shows the impact point should further damage make this difficult to confirm. The strawboard mounted behind is designed to capture any of the bullets which are deflected beyond and out of the helmet. The footage from the high-speed camera is used to calculate both the peak temporary and the peak permanent deformations in each case.

Figure 4. Plan View of Test Configuration

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4.1 Part 1: 25 mm from edge of helmet shell

The first part of the trial was to conduct the edge shot testing at 25 mm from the edge of the helmets at four positions around the helmet. These were at the front, rear and both sides. For Part 1 of the trial each helmet also had a 5th shot placed at the crown, to confirm that the helmet behaved as expected well away from the edges.

Table 2. Ballistic Helmet Test Results for Part 1 (25 mm from edge)

Helmet ID	*Shot No*	*Impact Point (Distance from edge, position)*	*Bullet Impact Velocity (m/s)*	*Outcome (N/P)*	*Peak Temporary Deformation (mm)*	*Peak Permanent Deformation (mm)*
PA1	1	25 mm, front	406	N	91	8
	2	25 mm, rear	419	N	79	16
	3	25 mm, RH side	416	N	79	12
	4	25 mm, LH side	407	N	90	14
	5	Crown	405	N	25	8
PE1	1	25 mm, front	408	*P*	96	82
	2	25 mm, rear	415	N*	84	70
	3	25 mm, RH side	405	N	74	37
	4	25 mm, LH side	417	N	96	55
	5	Crown	413	N	65	35

N* - bullet broken up, with at least one part of the jacket leaving the helmet edge

The results above show that at 25 mm from the edge both helmets provided a good resistance to perforation. The 1st impact on helmet shell PE1 slightly missed the aim point and was at approximately 22 mm from the edge. Therefore, it is assumed that both helmet materials will provide predominantly non-perforations at 25 mm from the edge. One important point to note at this stage, is that although the temporary deformation of both helmets was of a similar magnitude, the para-aramid helmet recovered to a lower permanent deformation.

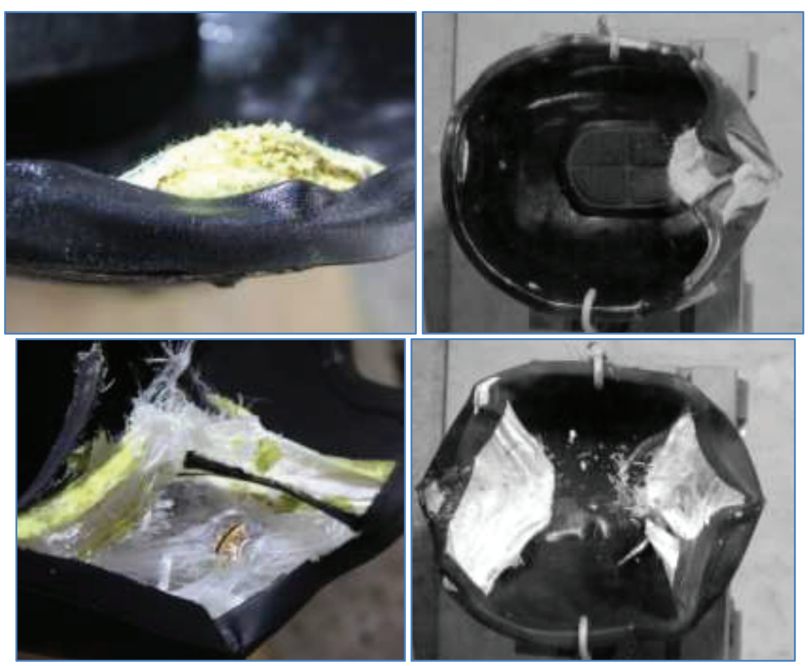

Figure 5. Shot 2 on para-aramid helmet PA1 (top) and Shot 2 UHMWPE helmet PE1 (bottom): permanent deformation (left); high-speed still of temporary deformation (right).

Figure 5 clearly shows the difference between the permanent and temporary deformation for the two helmet shell materials.

In order to add to the understanding of the perforation / non-perforation effects upon the bullets, the post-test helmet shells were X-rayed, as shown in figure 6. The figure also shows the greater delamination, withing the larger permanent deformation for the UHMWPE helmet. The X-rays give a clear indication of the differences in the deformation of the bullets between the para-aramid and UHMWPE helmet shells and show that one of the bullets in the UHMWPE shell was broken up.

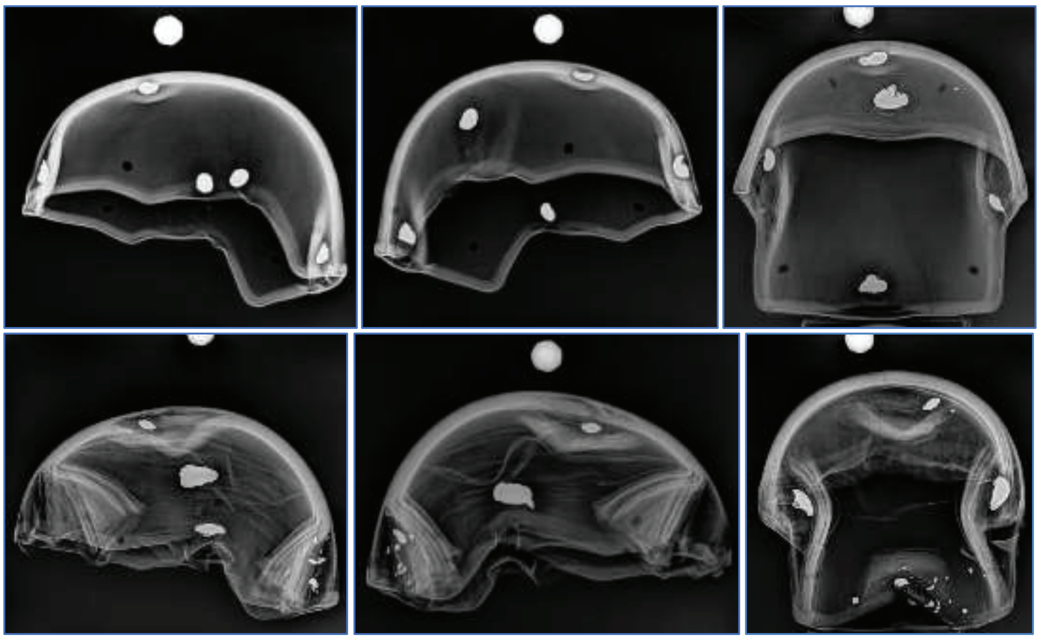

Figure 6. X-Rays of Para-Aramid Helmet PA1 (upper) and UHMWPE Helmet PE1 (lower) – Post-Test

4.2 Part 2: 15 mm from edge

Part 2 of the trial was a repeat of Part 1, but with the edge shots aimed at 15 mm from the edge. In this case, the majority of the shots produced perforations, with just one non-perforation on each helmet.

Table 3. Ballistic Helmet Test Results for Part 1 (15 mm from edge)

Helmet ID	*Shot No*	*Impact Point (Distance from edge, position)*	*Bullet Impact Velocity (m/s)*	*Outcome (N/P)*	*Peak Temporary Deformation (mm)*	*Peak Permanent Deformation (mm)*
PA2	1	Crown	416	N	21	5.2
	2	15 mm, front	405	P	72	n/a
	3	15 mm, rear	405	P	78	28
	4	15 mm, RH side	406	P	86	40
	5	15 mm, LH side	405	N	86	28
PE2	1	Crown	409	N	29	13
	2	15 mm, front	407	P	67	n/a
	3	15 mm, rear	404	N	118	109
	4	15 mm, RH side	413	P	65	42
	5	15 mm, LH side	403	P	76	75

Again these results show that there is little recovery of the shell material from temporary to permanent deformation with the UHMWPE shell, whereas there is significant recovery with the para-aramid one.

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Figures 7 and 8 show example shots from the para-aramid and UHMWPE helmets, respectively. The red circle on the high-speed still image for the para-aramid helmet (figure 7) shows the perforating bullet in flight across the helmet, as it drags fibres from the shell with it.

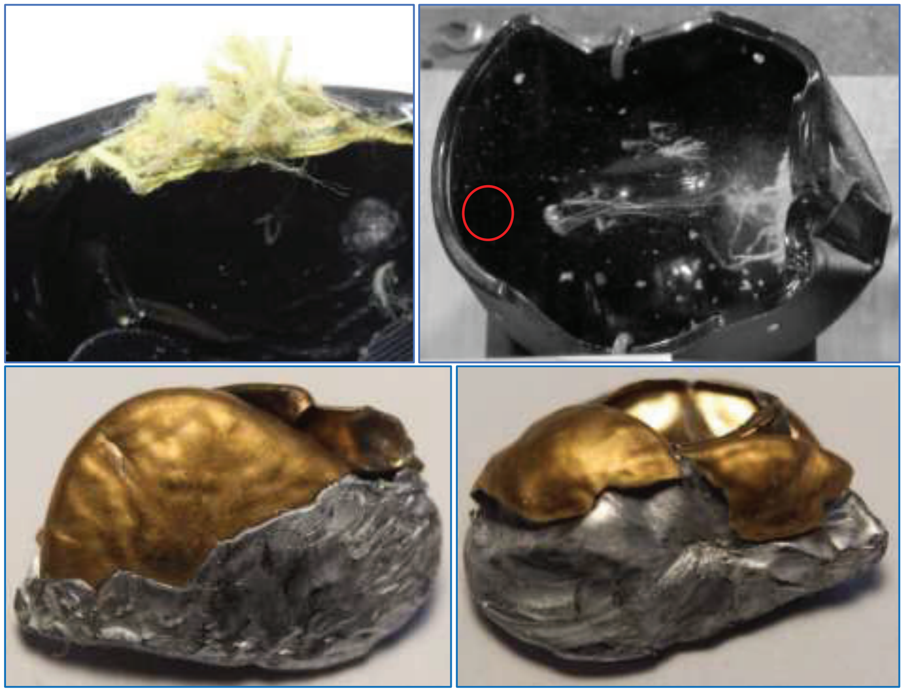

Figure 7. Shot 2 on para-aramid helmet PA2: permanent deformation (top left); high-speed still of temporary deformation (top right); recovered bullet (bottom)

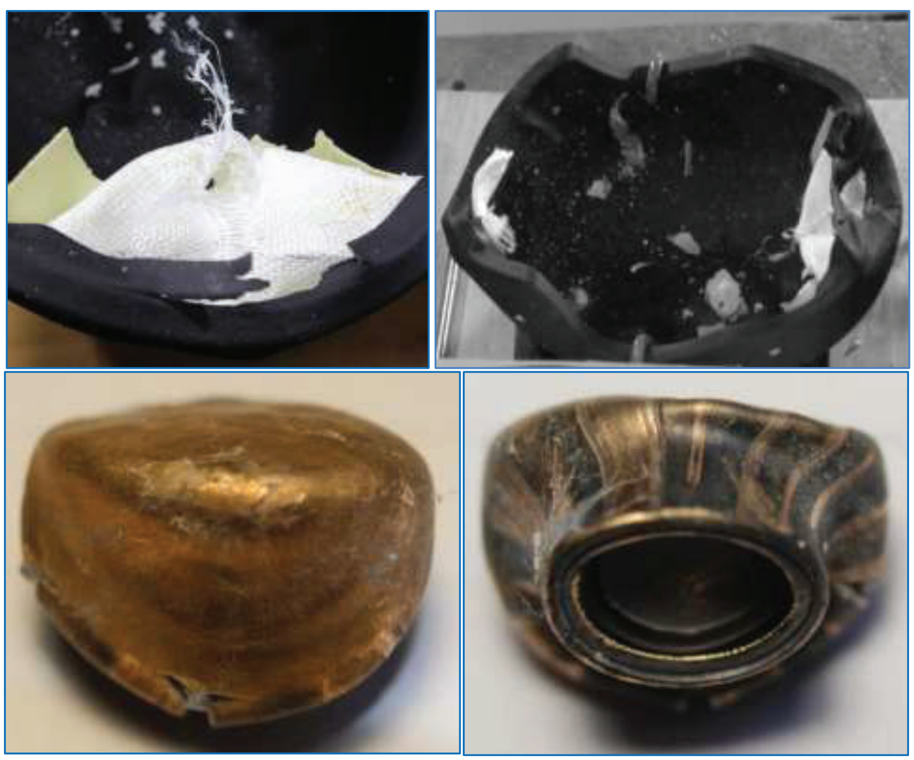

Figure 8. Shot 2 on UHMWPE helmet PE2: permanent deformation (top left); high-speed still of temporary deformation (top right); recovered bullet (bottom)

In order to add to the understanding of the perforation / non-perforation effects upon the bullets,, the post-test helmet shells were X-rayed, as shown in figure 9. These X-rays also show the much greater delamination of the UHMWPE shell than the para-aramid ones, as well as a greater tendency for break-up of the bullets with the UHMWPE shell.

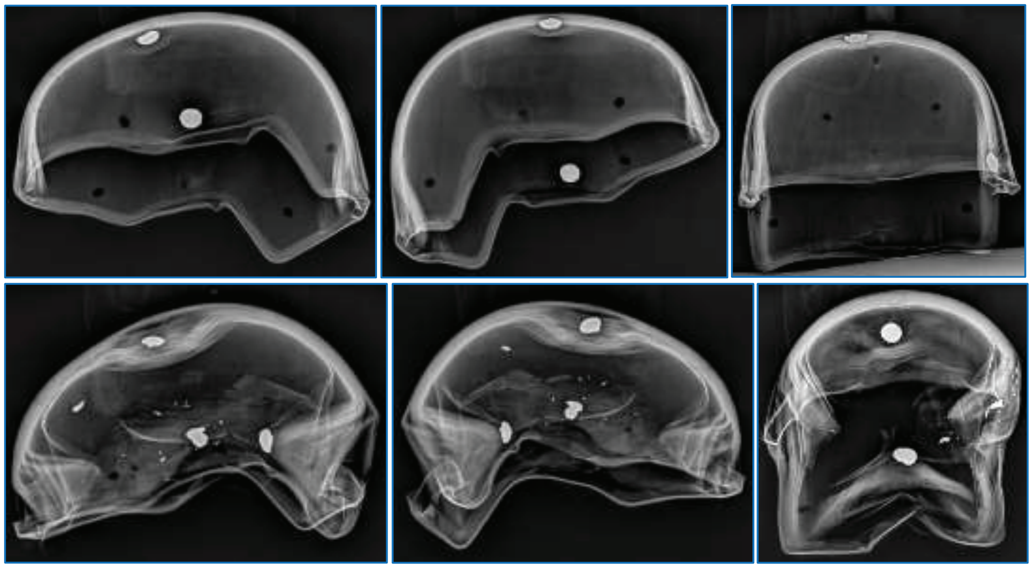

Figure 9. X-Rays of Para-Aramid Helmet PA2 (top) and UHMWPE Helmet PE2 (bottom) – Post-Test

4.3 Part 3: 20 mm from edge

With Part 1 at 25 mm from the edge producing predominantly non-perforations and Part 2 at 15 mm from the edge producing predominantly perforations, and bearing in mind that the VPAM HVN 2009 specified an edge shot at 20 mm, Part 3 of the trial conducted testing at 20 mm from the edge.

Table 4. Ballistic Helmet Test Results for Part 1 (20 mm from edge)

Helmet ID	*Shot No*	*Impact Point (Distance from edge, position)*	*Bullet Impact Velocity (m/s)*	*Outcome (N/P)*	*Peak Temporary Deformation (mm)*	*Peak Permanent Deformation (mm)*
PA3	1	20 mm, front	396	N	99	27
	2	20 mm, rear	392	N	92	52
	3	20 mm, RH side	391	P	80	25
	4	20 mm, LH side	401	P	90	28
PE3	1	20 mm, front	394	P	94	94
	2	20 mm, rear	395	P	92	85
	3	20 mm, RH side	392	P*	84	84
	4	20 mm, LH side	407	P*	79	79

P* - bullet broken up, with at least one part of the lead and the jacket exiting the helmet edge

At 20 mm from the edge there is a difference observed between the para-aramid and the UHMWPE helmet shells. For the para-aramid helmet, there has been an equal division between non-perforations and perforations. This outcome could be expected based upon the results for both 25 and 15 mm. For the UHMWPE helmet shell, all the impacts are considered to be perforations, although it is worth noting that two of the impacts broke up the bullet significantly and it was only part of the bullet that perforated. Figures 10 and 11 show equivalent shots 3 on each helmet material. Both of these shot 3s are considered to be perforations. Again, the para-aramid helmet has recovered from temporary to permanent deformation, whereas the UHMWPE helmet has shown no recovery from the temporary deformation.

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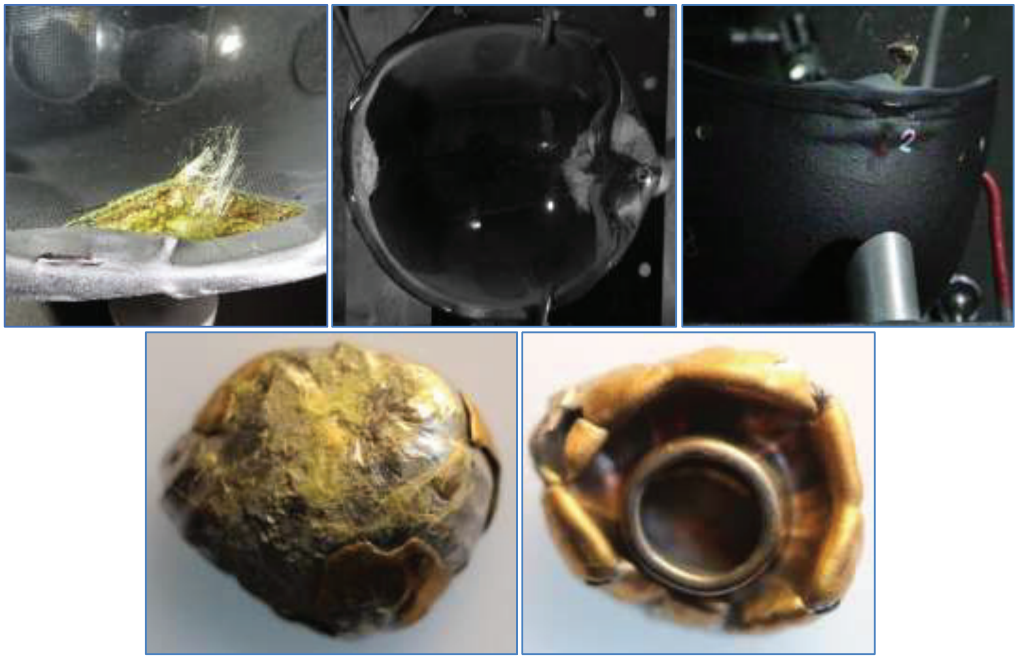

Figure 10. Shot 2 on para-aramid helmet PA3: permanent deformation (top left); high-speed still of temporary deformation (top right); recovered bullet (bottom)

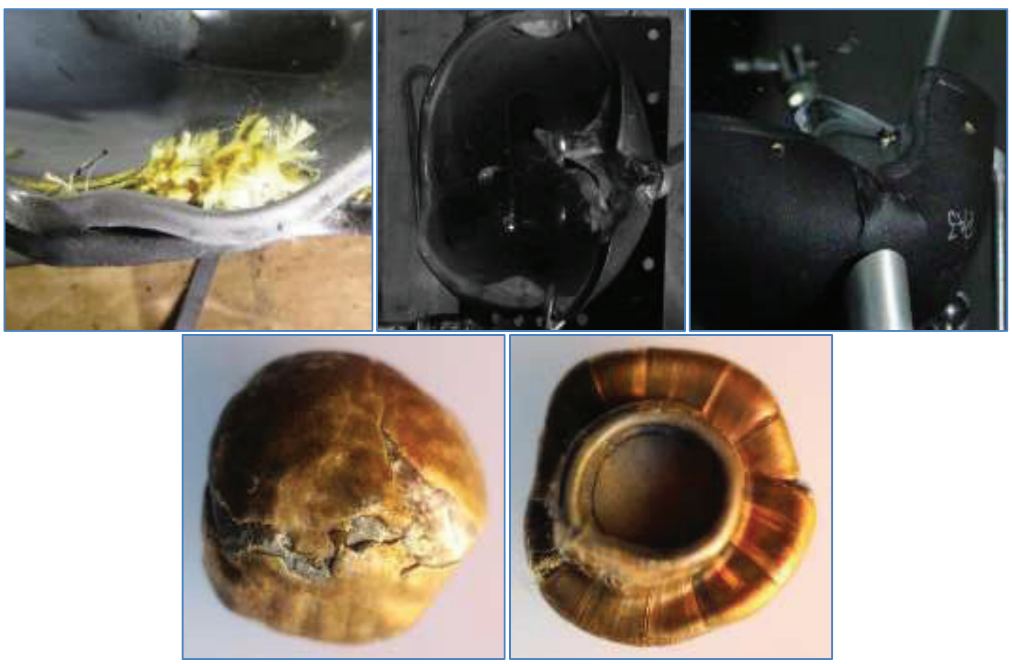

Figure 11. Shot 3 on para-aramid helmet PA3: permanent deformation (top left); high-speed still of temporary deformation (top right); recovered bullet (bottom)

Figures 12 and 13 show equivalent shots 2 on the two helmet materials. The para-aramid helmet shot 2 provided a non-perforation and exhibited significant recovery from temporary to permanent deformation. The UHMWPE helmet suffered a perforation and showed very little recovery from temporary to permanent deformation.

Figure 12. Shot 2 on UHMWPE helmet PE3: permanent deformation (top left); high-speed still of temporary deformation (top right); recovered bullet (bottom)

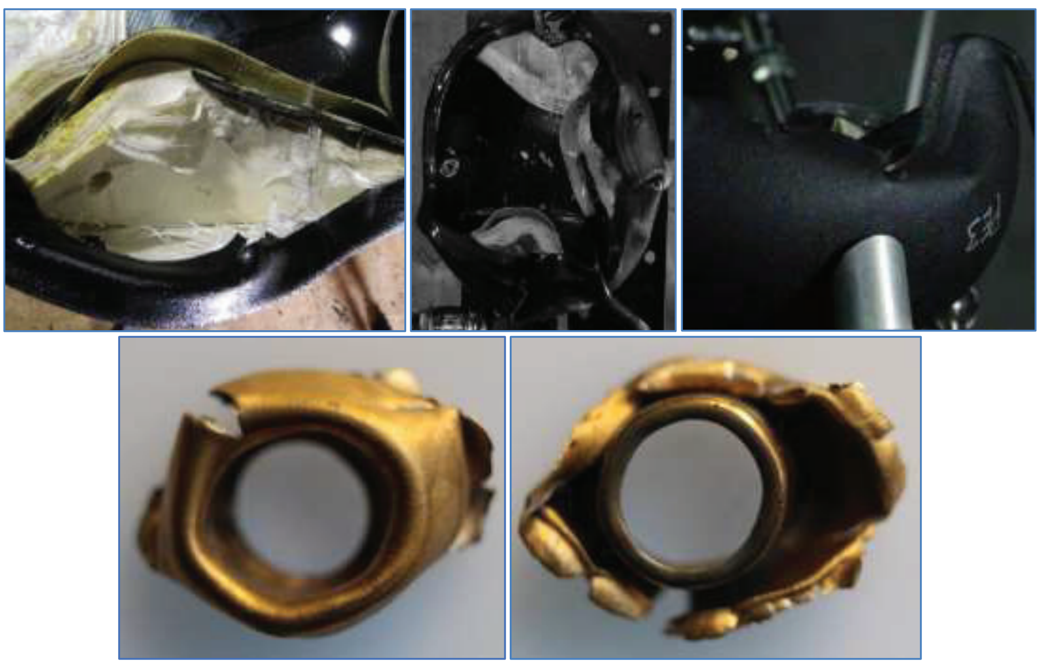

Figure 13. Shot 3 on UHMWPE helmet PE3: permanent deformation (top left); high-speed still of temporary deformation (top right); recovered bullet (bottom)

Figure 14 shows the X-rays for both para-aramid and UHMWPE helmet shells. The view of the para-aramid helmet indicates that all four edge shots were perforations. However, the first two shots left the helmet, not by perforating, or pushing aside the material, but by being pushed back and upwards by the recovering deformation. For the UHMWPE helmet, shots 3 and 4 (at the sides) show retained components of the broken-up bullet, but this was confirmed a perforation, as most of the jacket, in each case, perforated the shell material.

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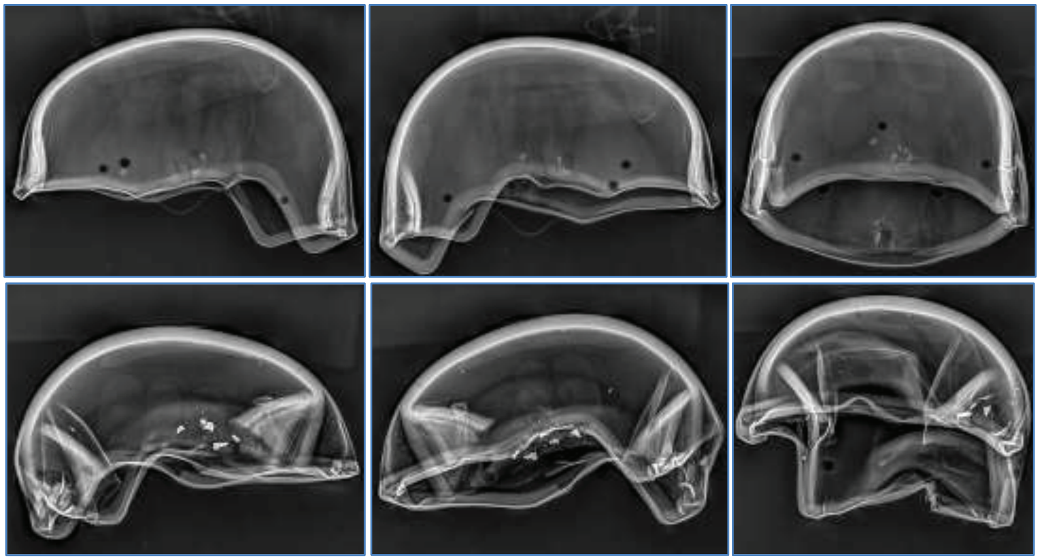

Figure 14. X-Rays of Para-Aramid Helmet PA3 (top) and UHMWPE Helmet PE3 (bottom): Post-Test

4.4 Discussion of High-Cut Ballistic Helmet Edge Test Results

One of the issues identified with the edge testing was the definition of what constitutes a perforation or a non-perforation. This issue was identified when the high-speed video was incorporated into the test method. With an impact at a greater distance from the edge it is obvious what constitutes a perforation or non-perforation, as there is either a hole in the material, or there is not. With edge impacts this is not so simple. In most cases the bullet continues its trajectory by pushing the material near the edge out of the way, without perforating it. Therefore, for edge performance a different definition of perforation and non-perforation is required. A perforation may be defined as a bullet continuing in a forward trajectory, and its lethality may need to be assessed using a witness material. These definitions have been used throughout these series of trials.

Bullet deformation in these pressed composite shapes tested (as opposed to soft body armour) demonstrated a wider variety of bullet deformation, with a number of irregular shapes. Some resulted in severe fragmenting of the bullet (most notable in the UHMWPE shells).

As the main objective of this study is to develop a suitable test method for the edge performance of helmets using inexpensive helmets as a development tool, (whilst making observations during the process), detailed discussion of the helmet performance at the different distances from the edge is not relevant to this paper.

4.5 Way Forward for Test Method

The test method developed with the inverted helmet and the two high-speed cameras has been shown to be viable and easy to conduct. Therefore, it is proposed as an on-going edge test within the MPS. In fact, it has already been used within a procurement tender for ballistic helmets.

Returning to the edge shot requirement within VPAM HVN 2009, it is felt that the 20 + 5 mm for an edge test is a target that should be achievable. However, rather than a single edge shot, it is proposed that one example of each helmet submitted is tested as here with edge shots to the front, rear and both sides, as the different locations may vary in performance.

References

[1] VPAM. ‘HVN-2009 - Test Guideline - Bullet-Resistant Helmet with Visor and Neck Guard.’ 2017.

[2] VPAM. ‘VPAM APR 2006 - General basis for ballistic material, construction and product testing - Requirements, test levels and test procedures’ Edition 2009