An experimental investigation into the threat posed by arrows to body armour

M. Seidl[1], K. Lehmann[2], and S. Grobert[3]

[1] *French-German Research Institute of Saint-Louis (ISL), 5 Rue du Général Cassagnou, 68300 Saint-Louis, Frankreich (marina.seidl@isl.eu)*
[2] *State Police Schleswig-Holstein, Mühlenweg 166, 24116 Kiel, Germany*
[3] *Bundeswehr Hospital Berlin, Scharnhorststraße 13, 10115 Berlin, Germany*

Abstract. Compound bows and crossbows are effective hunting tools and, hence, lethal weapons. Occasionally, light-protected security personnel, such as law enforcement officers and security guards, face attackers armed with archery weapons. While research has focused on the potential damage caused by bow attacks on the human body, limited work has been done to investigate the level of protection offered by body armour against such threats. This paper examines the performance of various types of body armour, including helmets and vests, against the impact of crossbow bolts. The study utilised a commercially available 300-pound (136 kg) draw weight crossbow and bolts with two different categories of penetration tips. Impact velocity was measured using a light barrier, and the body armour was fixed onto a 20% ballistic gelatine block serving as a backing. The bolts reached a velocity of 146 +/- 1 m/s after travelling a distance of 10 m, showing a very good repeatability during the tests. All tested body armour samples were found to be perforated, with the depth of penetration significantly influenced by the tip design. The aim of the study was to investigate the penetration depth and behaviour of bolts with two different penetration tips on body protection in the technically strongest case.

1. INTRODUCTION

Archery, dating back to 10,000 years, held significant importance in the armed forces. Bowmen, or archers, were considered superior due to the expertise required to handle such weapons. The invention of the crossbow in ancient China marked a significant shift in projectile weaponry. Its simplicity, affordability, and ease of use made it accessible to a large number of soldiers, including those with limited experience. Then, with the advent of firearms, archery gradually became obsolete in military applications during the 16th century; however, it experienced a revival in the late 18th century through the establishment of societies and competitions. Today, archery remains a popular sport, with crossbows widely used in shooting sports and hunting [1]. The growing popularity of archery [2] is evidenced by numerous private publications on social media showcasing arrow perforation on soft ballistic body protection.

2. PRELIMANARY RESULTS

The preliminary tests were conducted to validate the findings presented in open sources regarding the perforating power of arrows, particularly on soft ballistic protection. These tests employed a 70-pound (32 kg) compound bow on soft body protection.

The ballistic body armours were made of woven aramid layers and were launched perpendicular to the strike face. The preliminary tests conducted on the soft ballistic vests confirmed two findings. First, the type of arrow head significantly impacts the penetration depth. This is because hunting arrowheads with sharp edges exhibited lower penetration than solid penetration ones. The penetration tips, or sometimes referred to points, were used for all later impact configurations.

Second, the support provided to the soft body armour during impact is crucial. In these tests, a Styrofoam backing was used. Although Styrofoam is not representative of the human body, as it is too stiff, its influence on the arrowhead's penetration capability was evident, when observed in relation to no backing (**Figure 1**. a, b) [3].

https://doi.org/10.52202/080042-0046

a) Without backing b) With Styrofoam backing

Figure 1. Arrow with penetration tip perforates soft body armour

Upon impact, ballistic protection without a backing attachment on the body armour behaves differently from the human body [4]. Additionally, some energy dissipates into the pendulum motion of the body armour. Therefore, to represent a realistic and elastic background material, ballistic gelatine [5] was chosen for this study.

An unfavourable load case from an engineering perspective was chosen and a Ravin R500 compound crossbow, a commercially available crossbow, was selected for the experiments.

The bolts, referred to as arrows for the crossbow, were equipped with points similar to those that demonstrated the strongest penetration performance in the compound bow. Considering the significant influence of the backing on arrow perforation, particularly with soft ballistic body protection, ballistic gelatine was utilised.

2. METHOD AND MATERIALS

2.1 Crossbow

The tests were conducted using the Ravin R500 compound crossbow (**Figure 2**). The crossbow was operated with a manual cocking system and a magnifying glass (**Table 1**).

Figure 2. Ravin R500 compound crossbow

Table 1. Technical data of the crossbow

Component	Unit	Value
Draw weight	kg (lbs)	136 (300)
Mass (without scope)	kg	3.8
Length	mm (in)	710 (30)
Width	mm (in)	190 (7.5)

2.2 Bolts and tips

Ravin bolts were used. **Figure 3** depicts one of the used carbon bolts with a training point.

Figure 3. Bolt with training point

https://doi.org/10.52202/080042-0046

Figure 4 shows the bolt tips used. The topmost point of the first bolt represents the training point. Its ogival shape is designed to prevent excessive penetration into practice targets and facilitate easy removal. The middle bolt in the picture has a silver-coloured steel penetration tip. It features a groove after the conical tip and a gradual increase in cross-section to potentially enhance penetration into the target, referred to as 'penetration I' (PEN I). The last bolt represents another penetration tip with a longer first part and curved transitions leading to the largest cross-section, known as 'penetration II' (PEN II). These points are screwed onto the carbon bolt using threaded brass inserts.

Including the mass of tip, the bolt had a mass of 26 g with both the penetration tip and the training tip, and 27 g with the stainless steel penetration tip (**Table 2**).

Figure 4. Bolts with training point (top), penetration tip I (PEN I) (middle), and penetration tip II (PEN II) (bottom)

Table 2. Technical data of the bolts

	Unit	Value
Mass with training point	g (oz)	27 (1.0)
Mass with PEN I	g (oz)	26 (0.9)
Mass with PEN II	g (oz)	28 (1.0)
Length	m (in)	0.51 (20)
Diameter	m (in)	0.09 (3.5)

2.3 Velocity profile

A Doppler radar was used to record the initial velocity profile of the bolt with the penetration point. Four measurements were taken, and the bolt's velocities were recorded at 1 m, 5 m, 10 m, and 50 m (**Figure 5**). Each measurement was repeated three times and the velocity results varied by ±1 m/s. The velocity data in the blue curve are partially interpolated between 0 m and 50 m and extrapolated above 50 m. At 10 m, a velocity of 146 m/s was measured, which aligns with the light barrier measurement (**Figure 6**). After 50 m, the bolt had lost 10% of its initial velocity and was travelling at 136 m/s.

The resulting energy of the arrow is illustrated in the red curve. The bolt's initial energy was 300 J, approximately half the kinetic energy of a 9 x 19 mm FMJ Luger projectile with 415 m/s velocity.

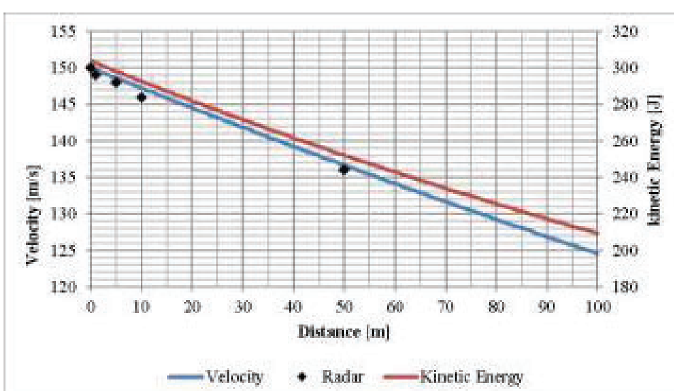


Figure 5. External ballistics of bolt (STANAG 2920 without error correction)

2.4 Target configurations

Eight different protective structures were considered for testing and varied in their protection class. **Table 3** provides an overview of the target configurations used. The protective structures used as the target configurations are classified according to the German technical classification [6]. The classification specifies different protection classes (German: Schutzklassen [SK]) ranging from 1, with protection against soft (lead core) 9 mm full metal jacket (FMJ), to 4, with protection against hard (steel) core rifle ammunition.

Protection class SK2 is certified for 9 mm hard-core bullet protection. In addition to the soft ballistic vest, this class requires an aramid in conjunction with (ICW) plate. A soft composite layer is also added to reduce behind armour blunt trauma (BABT).

Stab protection (German: Stichschutz [ST]) is achieved by using a metal foil or chain mail with ultra-high-molecular-weight polyethylene (UHMWPE) armour [7].

Table 3. Target configurations

Ref.	Configuration (from attack to body side)	Protection class*
1	ICW Plate + SK1 soft body armour + BABT reducing element	TR SK2 (German)
2	Standalone ICW aramid plate	none
3	Soft aramid layers + metal foil stab protection	TR SK1 ST (German)
4	Soft UHMWPE layers + metal chainmail stab protection	TR SK1 ST (German)

**Material parameters are under disclosure*

The ballistic body armour was placed on a 0.40 x 0.30 x 0.20 m block of 20% ballistic gelatine, which is internationally recognised as a representative soft tissue simulant [5]. The gelatine block was positioned upright and supported by wood (**Figure 7**).

2.5 Experimental setup

Figure 6 shows the schematic test setup. The shooting distance of 10 m was chosen based on international test standards for body armour, such as VPAM (Vereinigung der Prüfstellen für angriffshemmende Materialien und Konstruktionen) [8]. The crossbow (1) was treated as a rifle, and efforts were made to align the arrows with the target setup in an approximately perpendicular trajectory. The study did not consider the actual arrow angle incidence (yaw).

The velocities of the crossbow bolts were measured using a light barrier positioned 1.5 m ($v_{1.5}$) in front of the target (2). A coloured high-speed camera (3) captured the bolt impact on the protective body armour and the gelatine block (4).

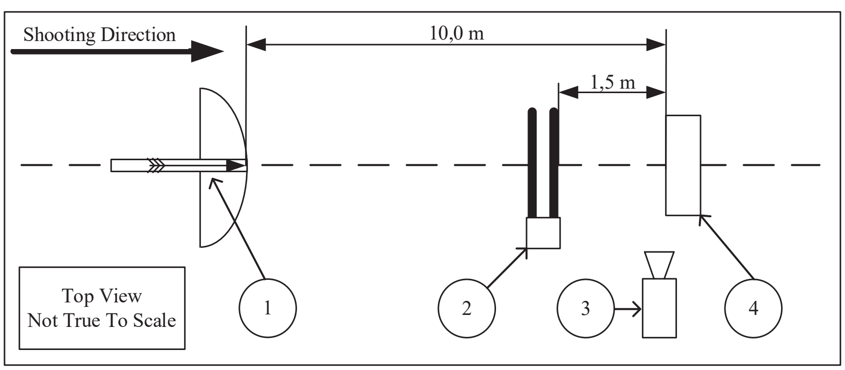


Figure 6 Schematic representation of experimental setup

3. RESULTS

Table 4 starts with the highest certified ballistic protection and is lowered step by step, as was described in **Table 3**. Different bolt tips were used for the different target configurations (**Figure 4**). The velocity is given by its reproducibility as an average value, as well as the resulting kinetic energy E (**Figure 5**). The bolt's impulse was derived.

The target perforation was considered when the bolt point was visible at the back face of the target, while penetration in the gelatine was determined by observing surface damage.

https://doi.org/10.52202/080042-0046

Table 4. Bolt penetration results

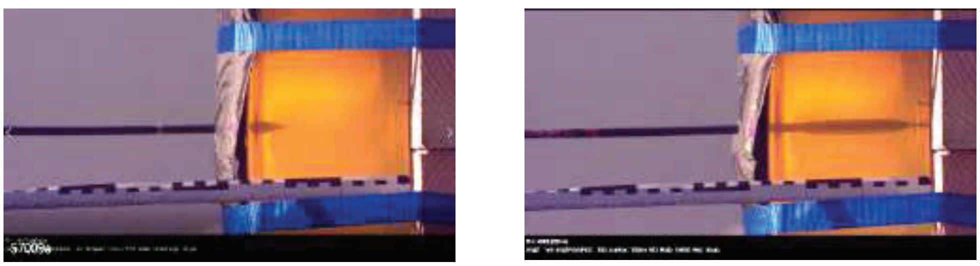
Test ID	Target config.	Tip	Velocity v [m/s]	Energy E [J]	Impulse I [Ns]	Target perforation	Gelatine penetration
A	3	PEN II				Yes	Yes
B	4	PEN II				Yes	Yes
C	1	PEN II				No#	No
D	1	PEN II	$147^{\pm 2}$	$292^{\pm 8}$	$3{,}97^{\pm 0{,}068}$	Yes	No
E	1	PEN I				Yes	No
F	Helmet	PEN II				Yes	Yes
G	Helmet	PEN II				Yes	Yes
H	Helmet	PEN II				Yes	Perforation

#*Perforation of ICW plate only*

3.1 Test A: Soft ballistic body armour with metal foil

The bolt with the PEN II penetration tip impacted the soft ballistic body armour, which consisted of aramid layers and a metal foil for stab protection (**Table 3**, Target configuration 3).

Figure 7 shows the high-speed camera images depicting the impact on the ballistic gelatine at time t and t + 0.8 ms. Both the body armour and the 0.2 m thick gelatine were perforated, with the bolt being stopped by the wooden backing (**Figure 7** b). The bolt created a circular hole in the body armour.

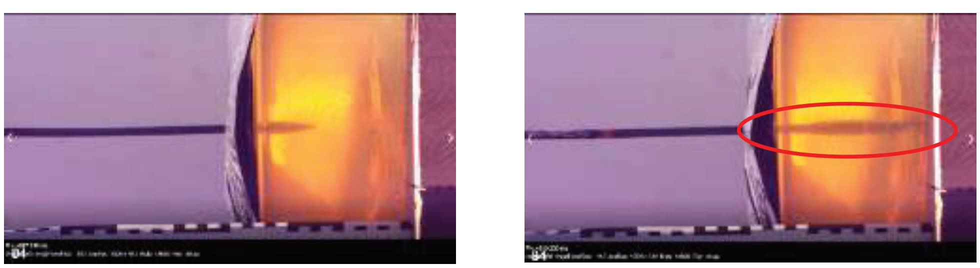


a) Impact at t b) Impact at t+0.8 ms

Figure 7. Bolt PEN II perforates soft ballistic body armour with stab protection foil

3.2 Test B: Soft ballistic body armour with chain mail

The bolt with the PEN II penetration tip was launched at 146 m/s onto the soft ballistic body armour (**Table 3**, Target configuration 4), which was supported by chain mail for stab protection. **Figure 8** shows the images of the perforation in the body armour at t = 0 and 0.7 ms. The full length of 0.2 m gelatine was perforated, and the bolt was stopped by the wooden backing (**Figure 8** b).



a) Impact at t = 0 ms b) Impact at t = 0.7 ms

Figure 8. Bolt PEN II perforates soft ballistic body armour with chain mail stab protection

Figure 9 shows the chain mail damage, with the failure of a single link. The bolt impact bent the link, leaving an unprotected area large enough for the bolt to penetrate the soft ballistic protection [8].

https://doi.org/10.52202/080042-0046

a) Perforated body armour b) Broken chain link

Figure 9. Damage of the chainmail upon perforation of a bolt with PEN II at 146 m/s

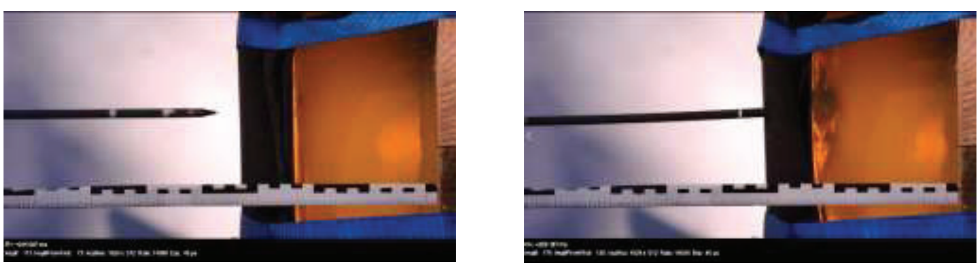
3.3 Tests C and D: Hard ballistic armour (SK2)

Test C (**Table 3**, Target configuration 1) examined the influence of yaw angle on the bolt's perforation capability. The bolt with the penetration tip PEN II impacted with yaw relative to the flight axis (**Figure 10** a). It perforated the aramid ICW plate but not the soft ballistic body protection behind it (**Figure 10** b). Due to oblique shear stresses on the longitudinal axis, the arrow broke directly at the protective plate.

a) Impact at t = 0 ms b) Impact at t = 1.6 ms

Figure 10. Bolt PEN II penetrates SK2 body armour at impact with yaw

In Test D (**Table 3**, Target configuration 1), high-speed imaging showed a perpendicular impact without bolt nutation (**Figure 11** a), resulting in perforation of the ballistic body protection and complete penetration of the gelatine block until the bolt was stopped by the wooden backing (**Figure 11** b).



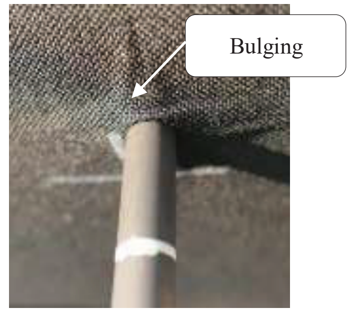
a) Impact at t = 0 ms b) Impact at t = 4.5 ms

Figure 11. Bolt PEN II perforates SK2 body armour at perpendicular impact

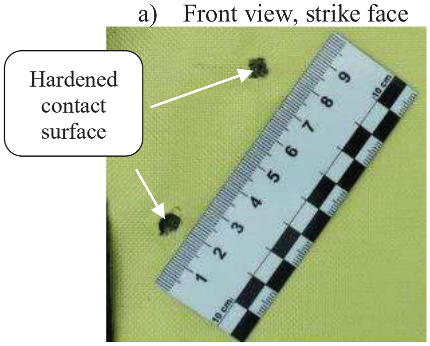
On the strike face of the protective plate, relatively small material bulges caused a permanent deflection (**Figure 12** a, b). No pronounced delamination was observed in the protective plate.

In the soft ballistic protection package, a clear material displacement was observed around the area where the bolt perforated the soft armour (**Figure 12** c). The contact surfaces of the bolt were hardened and raised (**Figure 12** d).

https://doi.org/10.52202/080042-0046



a) Front view, strike face   b) Material bulging

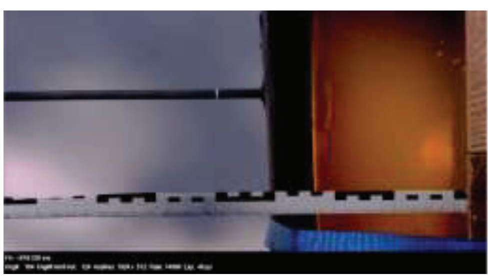


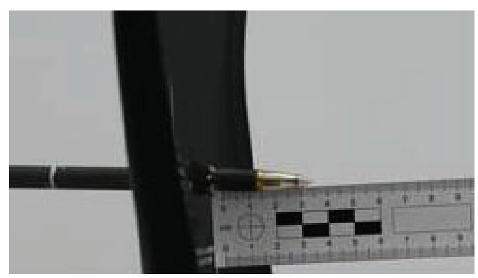
c) Soft armour behind plate   d) Contact surfaces of plate with bolt

Figure 12. Damage signature on hard ballistic body armour SK2

3.4 Test E: Exploration of the influence of the bolt penetration tip

The steel penetration tip (PEN I) was launched towards the target configuration (**Table 3,** Target configuration 1) at a constant velocity of 146 m/s from a 10 m distance. The bolt followed a straight flight path and perforated the target but not the gelatine block (**Figure 13** a). PEN I exhibited 40% less depth of penetration than PEN II under the same conditions (**Figure 13** b).





a) High speed image of impact   b) Penetrated plate

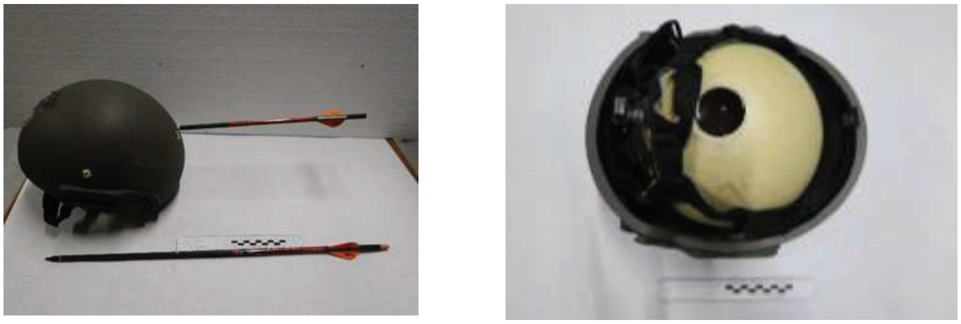
Figure 13. Bolt PEN I perforates ICW plate at 149 m/s

3.6 Tests F, G, and H: Helmets

Three types of combat helmets were tested. The bolts with PEN II were launched at $v_{1.5}$ = 146 m/s from a distance of 10 m.

A head simulant, consisting of a spherical skull substitute filled with 20% gelatine, was fixed inside the helmet using helmet straps (**Figure 14** b). The bolt perforated the helmet and the skull simulant [9, 10].

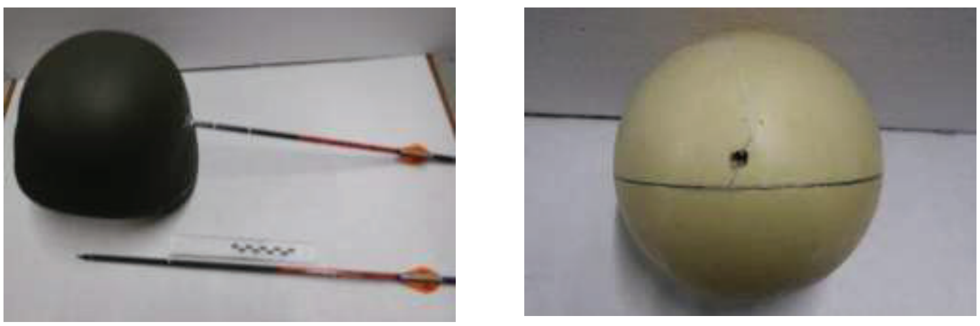
In Test F (**Table 4**), the helmet has the classification of VPAM 3 (9 mm FMJ, E < 25 J) lead bullet [9] and was impacted parietally by the bolt with the velocity $v_{1.5}$. The bolt perforated the helmet shell and interior and penetrated the head simulant (**Figure 14** a).



a) Parietal bolt impact b) Head simulant inside the helmet

Figure 14. Bolt PEN II perforates parietally a VPAM 3 aramid combat helmet

In test G (**Table 4**), a standard aramid shell was impacted laterally (**Figure 15** a). The lateral position was the most straightforward to test on this helmet model. Further tests would be required to determine the influence on the damage to the head simulant between the impact positions on the helmets and models. The bolt perforated the helmet and penetrated the head simulant. The damage to the head simulant for this test is represents the results of tests F and H, respectively (**Figure 15** b).



a) Lateral bolt impact b) Head simulant damage signature

Figure 15. Bolt PEN II perforates laterally a standard aramid combat helmet

Test H (**Table 4**) involved a light combat helmet made of UHMWPE. The helmet was perforated at the parietal region (**Figure 16** a). The bolt perforated the helmet and the head simulant. The head simulant had an entry hole damage signature as described in the prior test G (**Figure 15** b) and petaling failure on the exit. The helmet showed delamination on the inner layers, which was not observed in the previous test configurations and clean cut hole on the strike face (**Figure 16** b).

a) Parietal bolt impact b) Helmet damage signature

Figure 16. Bolt PEN II perforates parietally an UHMWPE helmet and the head simulant

4. DISCUSSION

The Ravin R500 compound crossbow was chosen because it is commercially available and comes with basic equipment. The mechanical crank had a loading time of approximately 30 seconds. While there are gadgets that speed up the loading process, they were not included in this study. The crossbow

https://doi.org/10.52202/080042-0046

was placed on a mounting block and launched by hand, so precision and accuracy were not emphasised in this study. The bolts were launched perpendicular to the target surface.

The velocity $v_{1.5}$ of the bolts was determined for each shot with light barrier placed 1.5 m before the strike face and had an error band of $v_{1.5} \pm 2$ m/s. In a free flight test, the bolt was tracked using radar. After 10 m, the bolt had a velocity of 146 m/s, verifying the measured $v_{1.5}$ form the light barrier results. It was observed that the velocity dropped by 10% after 50 m. Due to the high length-to-diameter (L/D) ratio, arrows or bolts are less affected by drag, allowing them to maintain their velocity over longer distances. However, this high L/D ratio can impact flight stability. It was demonstrated that the inclination of the bolt influences its penetration capability upon striking the target. It is noteworthy that the strong angle of incidence occurred only in one test.

The bolts were equipped with two different penetration tips, either the PEN I, or the PEN II. These specially shaped tips have a two-fold gradual increase in the overall diameter of the arrow. Due to the sharp tip, which maintains its shape and does not deform upon entry, there is a consistent and high cross-sectional load on the arrow throughout penetration. After perforating the material, the arrow can slide off the first level and further enhance its penetration ability on the second level. This occurs under a lower cross-sectional load but under a constant, powerful thrust of the heavy arrow. As a result, arrows can bypass the protective properties of vests and helmets, similar to hard-core bullets from higher protection class handguns. PEN II demonstrated the highest capacity to penetrate the body armour.

The soft body armour backing consisted of a 20% gelatine block. The gelatine block size was estimated to represent the size of a medium sized male torso. The torso shape was not considered, as the gelatine block was primarily for most accurate representation of a backing material. Therefore, additional clothing and skin that would have an influence on the penetration, was not considered.

The first two tests (Test A and B) were performed using soft ballistic body armour with gelatine backing. One piece of soft ballistic body armour was equipped with a metal foil for stab protection, while the second one had chain mail. In this experimental setup, the influence of stab protection, whether it be metal foil or chain mail, on the penetration of the bolt was not observed. Next, the hard ballistic body armour was tested (Test C and D). Despite completely perforating the hard ballistic plate, the bolt was stopped at a shooting distance of 10 m. Based on these results, it was expected that bolts would penetrate a helmet.

Consequently, the depth of penetration into helmets was investigated. The bolts perforated the helmets and penetrated the skull simulant. In the case of the UHMWPE helmet, the bolt also perforated the skull simulant. The observed crack lengths in the skull simulant were approximately comparable to those caused by 9 x 19 mm FMJ bullets in gelatine. This indicates a risk of injury beyond the penetration zone, reaching into the surrounding tissue. It is noteworthy that this temporary cavity occurred even after the protective plates in the gelatine block were penetrated, suggesting a high effectiveness of the bolts.

Although bolts are slower and have roughly half the kinetic energy of a 9 x 19 mm FMJ bullet, their rigid tip allows them to penetrate the protective body armour. Their end-ballistic properties differ from those of bullets, and the energy dissipating mechanisms of the target material fall somewhere between traditional penetration (stabbing) and bullet ballistics.

5. CONCLUSION

From a terminal ballistic perspective, the high repeatability and relatively easy handling make crossbow an interesting threat to test body armour. It does not require pyrotechnic considerations, and different bolt tips exhibit distinct failure patterns, which provide valuable insights into material modelling.

The velocity range of 100–150 m/s is not typically tested and gives an insight on a underrepresented load case, helping for better understanding on the material behaviour and therefore, to better body protection design in the future.

The experimental set-up was chosen to investigate penetration and perforation of hard and soft ballistic armour. However, the chosen crossbow had too much energy and questions for instance of how much a chainmail protects the wearer could not be answered within this set-up. A thorough investigation on material behaviour and damage requires a lighter crossbow with around 100 - 200 pound draw weight would be sufficient within the experimental set-up described in this study.

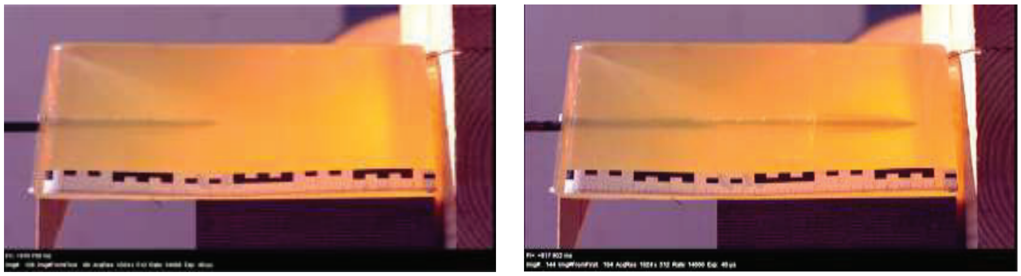
Radar measurement showed that a bolt loses 10% of its initial velocity during flight over a distance of 50 m and based on the results, implying that soft ballistic armour and helmets are perforated within this range.

Finally, it can be stated, that the crossbow represents an impact case which could be taken into consideration for future experiments.

6. RESEARCH RECOMMENDATIONS

Figure 17 illustrates the depth of penetration of the bolt launched with the penetration point. Two blocks of 20% gelatine, totalling 0.8 m in length, were used. The bolt is visible at the back face of the second block.

In future investigations, the resulting injury patterns, particularly the temporary processes during bolt penetration, will be examined, along with the observed crack lines [12].



a) Impact at t = 0 ms b) Impact at t = 1.1 ms

Figure 17. Depth of penetration test in gelatine

Acknowledgments

The Authors would like to thank the Police Berlin and the German Federal Police for their support.

References

[1] T. R. Whitman, The History of Archery, US: CreateSpace Independent Publishing Platform, 2017.

[2] A. Eriksson,WOR B. Georén and Ö. M., "Work-Place Homicide by Bow and Arrow," *J Forensic Sci,* vol. 45, no. 4, pp. 911-916, 2000.

[3] T.-T. N. Nguyen, H. Tsukada, J. Breeze and S. D. Masouros, "The Critical Role of a Backing Material in Assessing the Performance of Soft Ballistic Protection," *Hum Factors Mech Eng Def Saf,* vol. 6, no. 13, pp. 1-11, 2022.

[4] N. MacPhee, A. Savage, N. Noton, E. Beattie, L. Milne and J. Fraser, "A comparison of penetration and damage caused by different types of arrowheads on loose and tight fit clothing," *Sci. Justice,* vol. 58, no. 2, pp. 109-120, 2018.

[5] B. P. Kneubuehl , R. M. Coupland , M. A. Rothschild and M. J. Thali, Wound ballistics basics and applications., Berlin:: Springer, 2011.

[6] DHPol/PTI, Ballistische Schutzwesten, Technische Richtlinie (TR), Muenster, GER: Polizeitechnisches Institut (PTI) , 2008.

[7] VPAM-KDIW, Stab and Impact Resistance, www.vpam.eu: Association of test laboratories for bullet resistant materials and constructions, 2011.

[8] VPAM-APR, General Basics of Ballistic Material,Design and Product Tests, www.vpam.eu: Association of Test Laboratories for Attack Resistant Materials and Constructions, 2021.

[9] VPAM-HVN, Durchschusshemmender Helm mit Visier, www.vpam.eu, 2009.

[10] M. J. Thali, B. P. Kneubuehl and R. Dirnhofer, "A ''Skin–Skull–Brain Model'' for the Biomechanical Reconstruction of Blunt Forces to the Human Head," *Forensic Sci.,* vol. 125, no. 1, pp. 195-200, 2002.

[11] A. M. Ruchonnet, Y. H. Tang and E. F. Kranioti, "Cranial Blunt Force Trauma in," *Forensic Sci.,* vol. 301, no. 1, pp. 350-357, 2019.

[12] J. C. Downs, C. A. Nichols, D. Scala-Barnett and B. D. Lifschultz, "Handling and interpretation of crossbow injuries.," *J Forensic Sci. ,* vol. 39, no. 2, pp. 428-445, 1994.

https://doi.org/10.52202/080042-0046