# $V_{50}$ Study of Light-Weight Body Armour Inserts under Angle Shot

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**Abstract.** Various ballistic tests are carried out on UHMW-PE inserts and plates at various angles from 0° to 30° NATO. The results show a decrease of the $v_{50}$ by 14 % for plates with 12.7 mm thickness. For this purpose, several body armour inserts are cut along the shot axis after ballistic testing with the 7.62 x 39 PS in order to measure the pattern and to investigate the damage of the PE layers in more detail. It is observed that especially at the angular shots with 20 - 30° NATO the damage mechanisms in the UHMW-PE-layers behave differently. The thickness of the zone that is pierced without deformation is significantly thinner than in the case of shooting with 0° NATO. This can be particularly seen at the decreased deformation of the projectile. At the same time, increased shear stresses initiate delamination of the middle PE layers earlier. The projectile is deflected parallel to the UHMW-PE layers, so that it experiences less resistance, and more residual energy has to be absorbed by the layers close to the body. It was found out that this effect does not occur for plates with higher thickness. The $v_{50}$ decreases just by 6 % for the same material with 1.1 mm higher thickness. The angle shot effect disappears for plates with thicknesses of 15.2 mm and 20.8 mm.

## 1. INTRODUCTION

Today's soldiers and law enforcement officers have an increasing need for body armour systems that provide the best possible ballistic protection, on the one hand. On the other hand, there is a huge demand of flexibility for any combat situation - as a driver, as a gunner, or in the field - in order to ensure the highest possible probability of survival as well as efficiency in the field. In order to cover various curvatures to provide an ergonomic shape of the hard ballistic, the issue of angular shots of UHMW-PE inserts is extremely important to consider. In this paper, investigations of the angular shots in the protection level VPAM Level 6 (7.62 x 39 PS) will be presented in order to better understand the mechanisms of the angular impact. In this context, the influence of the different thicknesses and PE materials will be considered in addition.

## 2. INFLUENCE OF ANGULAR SHOTS ON DAMAGE AFTER IMPACT

In recent years, an increasing number of bullet penetrations have been observed when testing UHMW-PE inserts at various angles although these inserts were already certified against shots at 0° NATO. For this reason, the resolution No. 23 was added to the VPAM to cover the additional requirement of angular shots [2].

In this test series, extensive ballistic tests of the lightweight PE inserts are carried out. On one hand, $v_{50}$ velocities are obtained from UHMW-PE laminates to determine the angular dependence of the $v_{50}$ (section 2.1). On the other hand, samples of a certified ultra-light weight body armour solution are cut to investigate both the deformation area of the laminate and the projectile (section 2.2). In the end, the influence of different PE materials and for each the response to an impact by 20° NATO is highlighted (section 2.3).

### 2.1 $v_{50}$ Pre-Tests

The influence of the shot angle on the ballistic limit $v_{50}$ is determined on the VPAM Level 6 certified body armour insert. To determine the $v_{50}$-values, 24 shots are performed for each of the firing angles 0° to 40° NATO and evaluated according to the Kneubuehl method [3].

Sample: UHMW-PE Laminate 1
Dimensions: 400 x 400 mm
Thickness: 12.7 mm
Number of shots per Plate: 8
Shot pattern: 120 mm triangle

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In Figure 1, the results of various $v_{50}$-values are presented, as the $v_{50}$ at 0° NATO is taken as 100 % - reference. The data of each $v_{05}$ (5 % probability of penetration) and $v_{95}$ are highlighted by the red and green graph. The $v_{05}$ needs to be considered as well, since it is possible that the angle of attack has an influence not only on the $v_{50}$, but also on the distance between $v_{50}$ and $v_{05}$. Furthermore, the $v_{05}$ is close to the $v_{stop}$ that is the crucial criterion for the certification in the end.
The $v_{50}$-values show a minimum at a shot angle of 20° NATO at which the value drops by 14 % compared to the $v_{50}$ at 0° NATO. The results of $v_{05}$ and $v_{95}$ comply well with that as all values have a minimum at 20° NATO as well. An increase of the ballistic resistance due to a larger line-of-sight can only be observed from 40° NATO on.

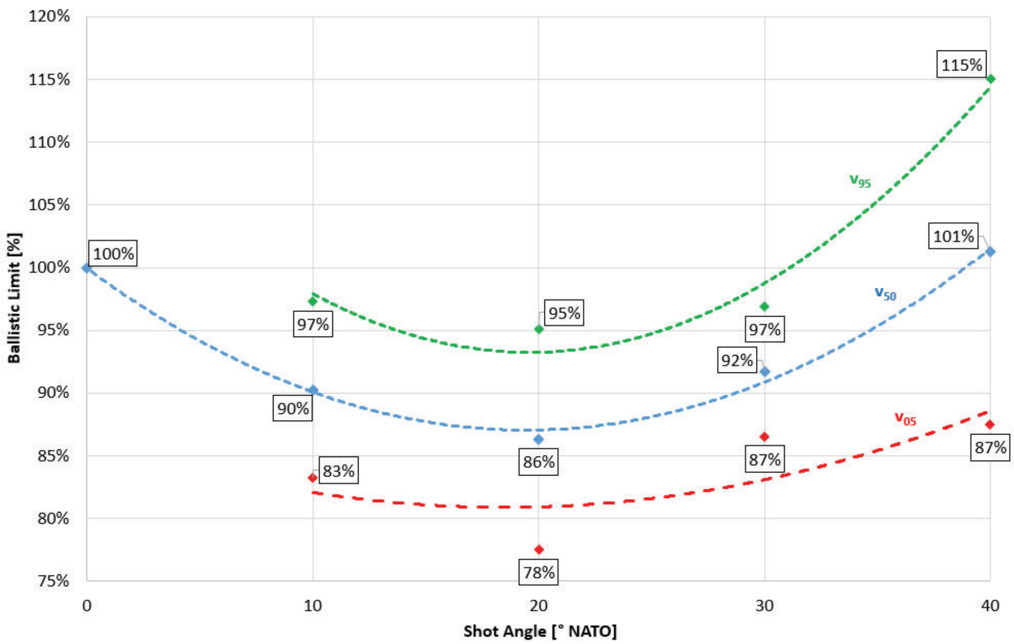


**Figure 1:** Laminate 1, Influence of the shot angle on $v_{50}$, $v_{05}$, and $v_{95}$; $v_{50}$ at 0° NATO is 100 % - reference

In order to ensure the resistance against angle shots, a new, slightly thicker and heavier UHMW-PE insert of the same material have been developed.

Samples: UHMW-PE Laminate 2
Dimensions: 400 x 400 mm
Thickness: 13.8 mm
Protection Level: VPAM BSW Level 6 incl. angle shots
Number of shots per Plate: 8
Shot pattern: 120 mm triangle

Despite the increase in thickness and weight, the measured total $v_{50}$-value of Laminate 2 is approximately as high as the $v_{50}$ of Laminate 1 at 0° NATO. In Figure 2, the test results of Laminate 2 are presented in the same manner as Laminate 1. The results show a minimum of the $v_{50}$ at 20° NATO and a lower $v_{50}$ at 10° NATO as well. However, the decrease of 6 % towards the $v_{50}$ at 0° NATO is much weaker compared to Laminate 1. At 30° NATO, the $v_{50}$ approximates the initial value. However, the course of the $v_{95}$ and $v_{05}$ deviates slightly from the courses of Laminate 1. $V_{95}$ shows at 10° NATO the same value as for 0° NATO. The course of the $v_{05}$ has even its minimum at 10° NATO.


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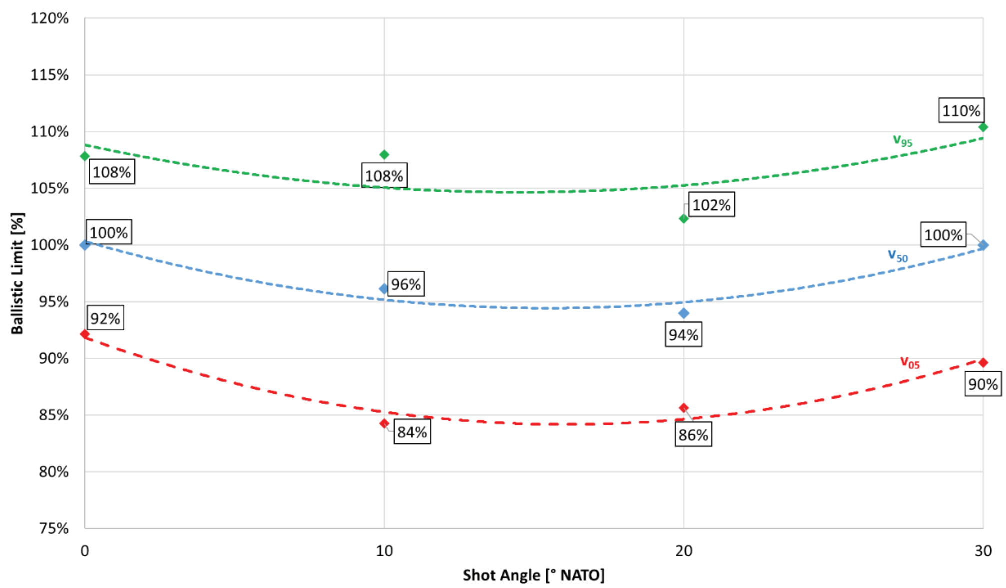


**Figure 2:** Laminate 2, Influence of the shot angle on $v_{50}$, $v_{05}$, and $v_{95}$; $v_{50}$ at 0° NATO is 100 % - reference

## 2.2 Ballistic Tests and Cutting of ultra-light weight Torso Plates

### *2.2.1 Samples and ballistic Testing*

To investigate the damage mechanisms in the PE after testing, an UHMW-PE ultra-light weight body armor insert is examined. The inserts have additional layers to reduce the trauma (BFS) and a textile cover. Therefore they have an increased thickness compared to the test samples in section 2.1. These inserts has been certified according to VPAM BSW Level 6 including the angular shots according to resolution No. 23. A scheme of the test setup is shown in Figure 3. Three shots on each insert were performed according to VPAM BSW Level 6. Table 1 gives an overview of the testing series. The tested samples are cut by water jet and the respective cross-section of the damaged area is examined.

Sample: UHMW-PE Ultra-light weight torso plate
Dimensions: 300 x 240 mm
Thickness: 18.5 mm (incl. trauma layer)
Weight: 0.98 kg
Number of shots per insert: 3
Shot pattern: 100 mm triangle
Protection Level: VPAM BSW Level 6

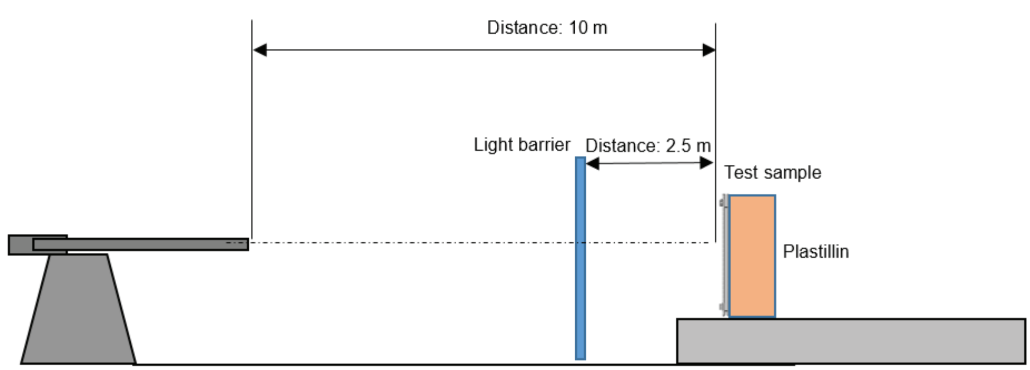


**Figure 3:** Schematic Test set-up of body armor inserts, according to VPAM BSW Annex 1 [1]

**Table 1:** Overview of samples

| | Shot angle [NATO] | Temperature |
|---|---|---|
| 1 | 10° / 10° | +20 °C |
| 2 | 10° / 10° | -20°C |
| 3 | 10° / 10° | +40 °C (95 % RH) |
| 4 | 10° / 10° | +70 °C |
| 5 | 20° / 20° | +20 °C |
| 6 | 20° / 20° | -20°C |
| 7 | 20° / 20° | +40 °C (95 % RH) |
| 8 | 20° / 20° | +70 °C |
| 9 | 30° / 30° | +20 °C |
| 10 | 30° / 30° | -20°C |
| 11 | 30° / 30° | +40 °C (95 % RH) |
| 12 | 30° / 30° | +70 °C |

### *2.2.2 Results of cut Samples*

According to various studies [4] [5] concerning the damage in laminated composites, the damage area can be divided in three zones during penetration of a projectile in an UHMW-PE laminate.

1. Compression of the uppermost layers during penetration of the projectile, first layers fail due to shear stress **(Zone 1)**
2. Delamination of the middle layers initiated by (micro-) crack **(Zone 2)**. Two mechanisms lead to cracking:
    a. Transversal shear: Superposition of interlaminar shear stress and transverse normal stress leads to 45° incipient cracking
    b. Deflection of posterior layers, high tensile stresses, can lead to cracks
3. Compression / Deflection of the rear layers (tensile stress) **(Zone 3)**

Considering these mechanisms, the thicknesses of the three zones are measured on the tested samples as a function of the angle of impact. As an example, the measurement of the zones is shown in Figure 4.

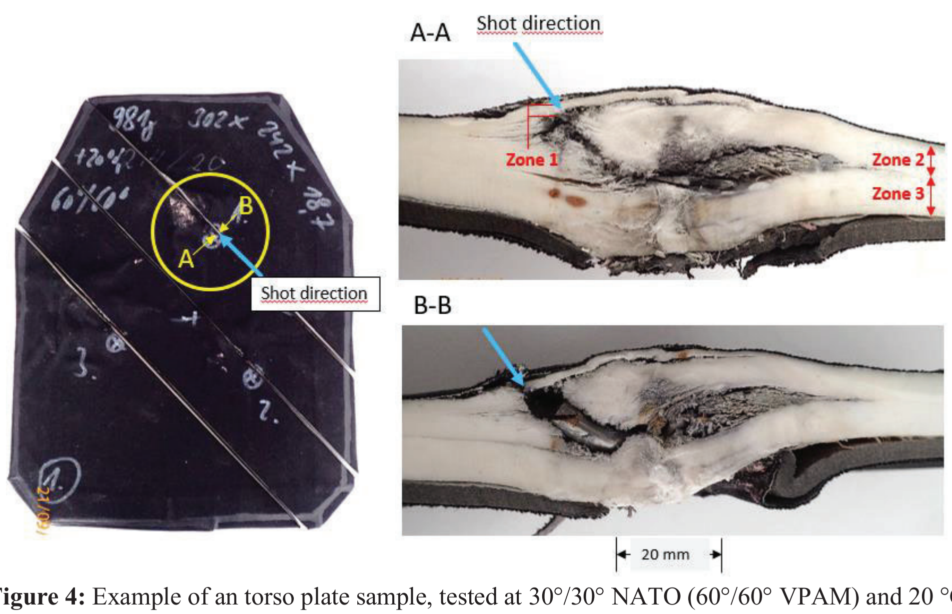


**Figure 4:** Example of an torso plate sample, tested at 30°/30° NATO (60°/60° VPAM) and 20 °C. Inserts were cut by waterjet, measurement of the zones

In Figure 5, the cross sections of the damaged area are shown as a function of the shot angle, while a sample tested at 0° NATO is added for reference. The pictures show that the projectile is deflected in the direction parallel to the laminate layers at 20° and 30° impact angles. As a result, a significantly wider delamination can be observed.


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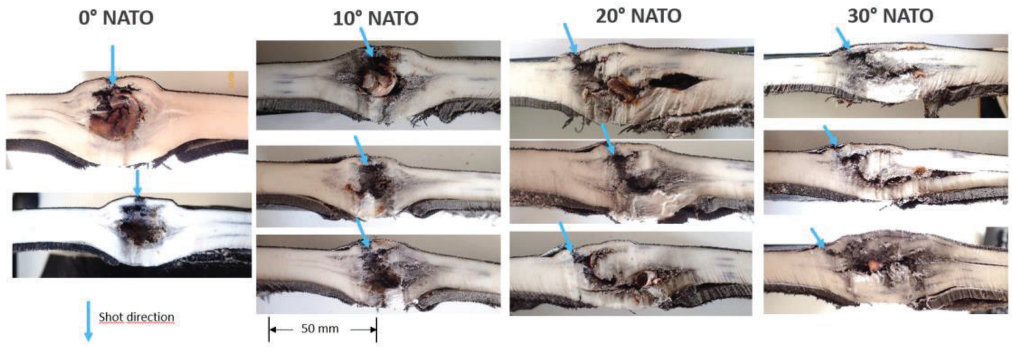


**Figure 5:** Cutting images of angle shot samples

The diagram in Figure 6 presents the relationship between the respective thickness of the three zones and the shot angle. It can be concluded that the angular shots lead to less compression, so a thinner zone 1, with a minimum at 20°. Through the deflection of the projectile the interlaminar shear stress is much higher. This leads to an earlier, larger and asymmetric delamination of zone 2.

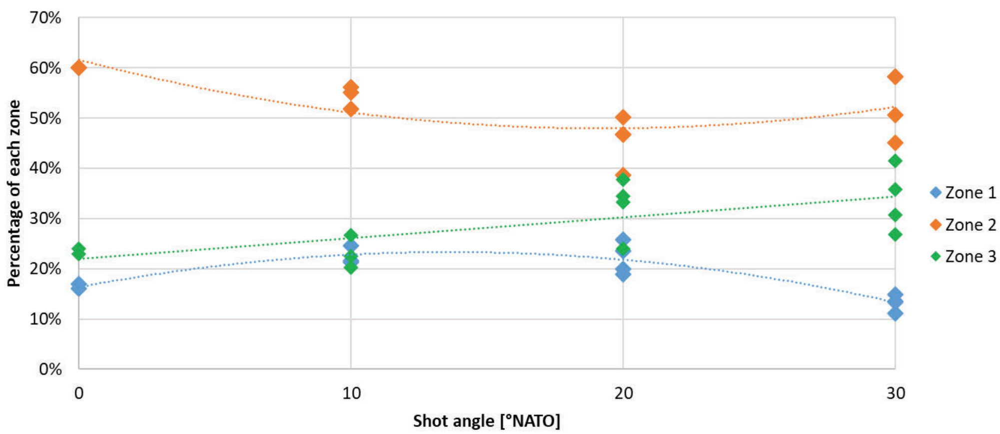


**Figure 6:** Thickness of zone 1-3 in depending on the shot angle

### *2.2.3 Results of Projectile Deformation*

The different deformation of the projectiles is shown in Figure 7. Due to the angular impact at 20° and 30° NATO on the surface, less perpendicular forces and at the same time higher shear forces affect the tip of procectile. Consequently, the projectile mushrooms asymmetrically, which even leads to a lateral sharp edge at 20° NATO. This edge might facilitate the penetrating and piercing of the laminate.
To describe the deformation, the length as well as the diameter of the mushroomed tip is measured (Figure 8). Figure 9 presents these measurement results as a function of the shot angle. The greater the angle of impact, the less the projectile is shortened by the impact and the less the projectile mushrooms. However, at 10° NATO the measurements show a deviation of this correlation. The length after impact is slightly lower than at 0° NATO and the mushrooming is even slightly higher. This can possibly be explained that the additional shear forces at 10° NATO contributes to the shortening and mushrooming of the projectile. Taking this into consideration, the total forces is increased which lead to higher mushrooming and reduction of length of the projectile.
A dependence of the damage on the test temperature cannot be observed in this test series.

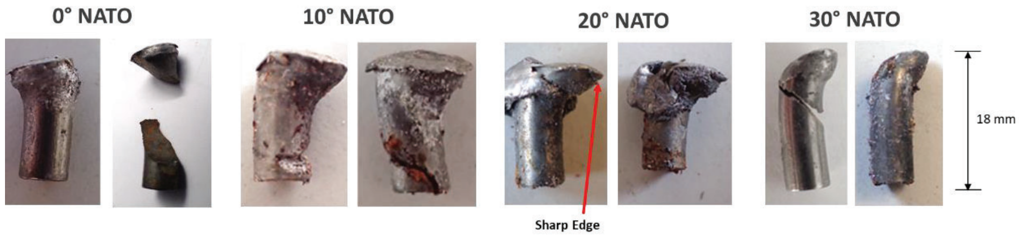


**Figure 7:** Projectiles after impact at different shot angles

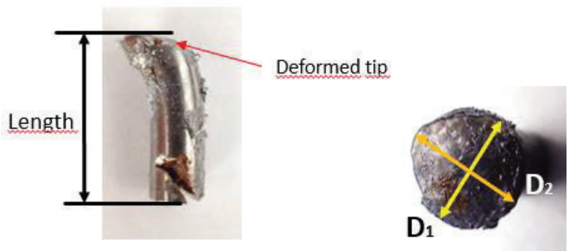


**Figure 8:** Measurement of length and diameters of the projectile after impact

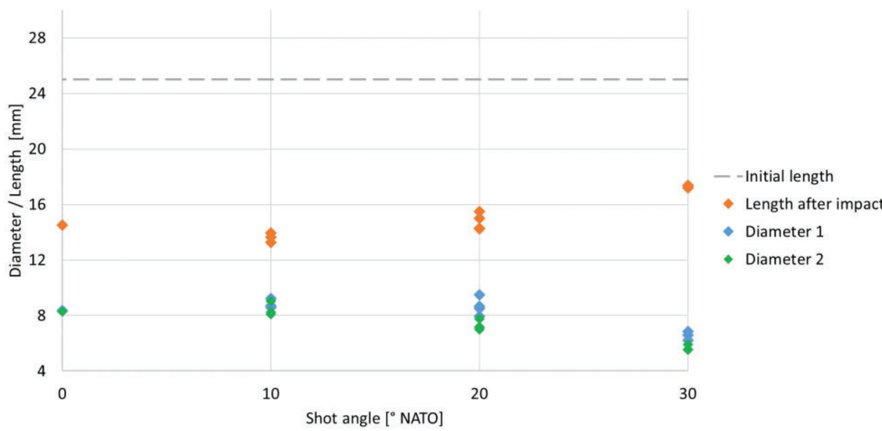


**Figure 9:** Angle dependence of diameter and length of the projectile after impact

### 2.3 Comparison of different UHMW-PE-Materials

Based on the results of the $v_{50}$ pre-tests, it was determined that the shooting at 20° NATO is the most critical and has the highest probability of penetration. In order to compare the performance of two different materials, the respective statistical values $v_{50}$ are determined. Applying the statistical evaluation according to the Kneubühl method [3] based on min. 16 shots, a sigmoid function can be generated for each material, which allows calculating the probability of penetration at different velocities. For this paper, the velocities $v_{50}$ and $v_{05}$ at 0° and 20° NATO are taken into consideration to investigate the shape of the sigmoidal curve in the context of the different UHMW-PE-materials. The two different materials have been expected to have very similar $v_{50}$-values.

Sample: UHWM-PE Laminate 3
Matrix: Rubber
Dimensions: 400 x 400 mm
Thickness: 15.2 mm
Number of shots per Plate: 8
Shot pattern: 120 mm triangles
Protection Level: VPAM BSW Level 6

Sample: UHWM-PE Laminate 4
Matrix: Polyurethane (PUR)
Dimensions: 400 x 400 mm
Thickness: 20.8 mm
Number of shots per Plate: 8
Shot pattern: 120 mm triangles
Protection Level: VPAM BSW Level 6

Figure 10 and Table 2 demonstrate the results of the $v_{50}$-tests taking the $v_{50}$-value of Laminate 3 as 100 % - reference into account. The two materials have the same $v_{50}$-value and show an increase of the $v_{50}$ and


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$v_{05}$ at 20° NATO. At the same time, the sigmoidal curves have a steeper course at 20° NATO, which is outlined by the decrease of the standard deviation by 2 %. By comparing the two different materials, the PUR Laminate have a slightly higher increase (3 %) of the $v_{50}$ and of the $v_{05}$ (6 %).

**Table 2:** Results of $v_{50}$-testing of Laminate 3 and 4 at 0° and 20° NATO

| | **Laminate 3 (Rubber)** | | **Laminate 4 (PUR)** | |
|---|---|---|---|---|
| | **0° / 0°** | **20° / 20°** | **0° / 0°** | **20° / 20°** |
| $v_{50}$ | 100 % | 102 % | 100 % | 103 % |
| $v_{05}$ | 91 % | 95 % | 91 % | 97 % |
| σ | 5 % | 3 % | 5 % | 3 % |

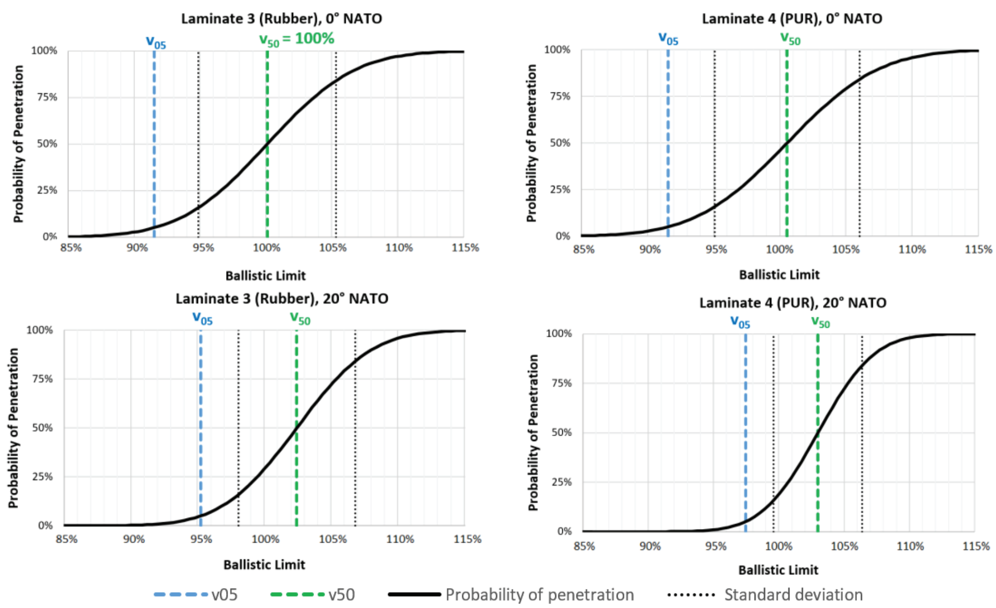


**Figure 10:** Sigmoidal Curves evaluated by Kneubuehl method of Laminate 3 and 4

## 3 DISCUSSION

The $v_{50}$-pretests of the lightweight Laminate 1 and 2 with thickness 12.7 mm and 13.8 mm show that the ballistic performance is the lowest at a shot angle of 20° NATO with a 14 %-decrease of the $v_{50}$. This can be explained by the different damage mechanisms due to the angular impact. Zone 1 decreases significantly so that the delamination initiates earlier and behaves asymmetrically. As the projectile is deflected nearly parallel to the layers it experiences much less resistance so there is a higher residual energy to be absorbed by zone 3. Additionally, the layers of zone 3 cannot deform in the same way and amount as under 0° NATO shooting, so that the energy absorption is even more impaired. Considering the projectile deformation, it can be concluded that the asymmetric mushrooming creating a sharp edge of the projectile tip amplifies this effect.

Regarding the thickness, both the results of Laminate 1 and 2 and of Laminate 3 and 4 indicate a dependency of the angle shot phenomenon with increasing thickness. By increasing the thickness of Laminate 1 it was found out that the susceptibility towards angle shots decreases. This is related to more layers of UHMW-PE layers which can stop the projectile in zone 3. Laminate 3 and 4 with thicknesses 15.2 mm and 20.8 mm do not show an dependency of the shot angle. There are enough layers in zone 3 to absorb the energy.

By comparing the two materials of Laminate 3 and 4, the $v_{50}$ of the PUR matrix material increases by 2 % more than the rubber matrix material. This could be a hint that the PUR matrix material is more resistant to the angle shot effect. However, Laminate 4 has a higher thickness by approximately 5 mm than Laminate 3. As outlined above, the angle shot effect decreases with higher thickness. The effect of a higher line-of-sight under angle can possibly lead to this larger increase of the $v_{50}$.

## 4 CONCLUSIONS

- By testing various UHMW-PE laminates (VPAM BSW Level 6) it was found out that the $v_{50}$ has a minimum at 20° NATO which is 14 % lower than at 0° NATO. For laminates with increased thickness, this phenomenon have a lower impact with just an decrease of 6 %.
- It was shown that the increased angles with 20-30° NATO lead to a thinner zone of the perforated initial layers of the PE laminate. The zone of delamination of the middle layers starts earlier and is larger. The projectile is deflected in direction parallel to the layers, so that it experiences less resistance by the PE layers.
- The projectiles themselves deform less and asymmetrically, which might even lead to a lateral sharp edge of the projectile.
- The angle shot weakness disappear at higher thickness at 15.2 mm and 20.8 mm.
- No clear evidence could be found that the material (PUR or Rubber) has an influence of the angular shot phenomenon.

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