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Determination of the Worst Case for the Ballistic Test of the Soft Armour System Using the 9mm FMJ Bullets Differing in the Structure

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Abstract
Ballistic tests require significant rigor and the development of a worst case model during the research processes. The purpose of this study was to evaluate the effect of bullet type (manufacturer) on V50 and Behind Armor Blunt Trauma (BABT) results for two ballistic applications: p-aramid and UHMWPE fibre. The results confirmed the thesis that the source of the bullets implies the test results obtained in terms of the number of penetrated layers in the ballistic system, backface signature deformation profiles (p-BFS) and the level of residual energy transferred to the user of the personal protection.

Keywords
bullet-proofness; BABT risk; V50; backface signature deformation profiles (p-BFS); backface deformation (BFD).

1. Introduction

The assessment of the safety of ballistic protection of the body is an important aspect related to their admission to use. For many years, it was conducted only in the field of ballistic tests allowing non-penetrated variants. During the design development of the above-mentioned products, parameters were introduced into the safety assessment, which indirectly verified the amount of energy transmitted to the user's body in the event of a non-penetrating shot on the body armour. This effect, called Behind Armour Blunt Trauma (BABT), represents the risk of injury to the user's body by transferring the impact energy of the projectile minus the amount of energy absorbed by the ballistic shield and the bullet deformation energy [1-2]. The value of BABT allows to estimate the risk of bone damage and lethal damage to viscera.

Table 1 summarises the criteria for verifying personal ballistic protection considering the parameters being evaluated. The risk of BABT is indirectly determined by the parameter of backface deformation (BFD) in the backing material that represents the user's body, caused by non-penetrating shots to the body armour. The above parameter is required in all major standards determining the quality and safety of ballistic materials, while the volume of deformation ($V_{deformation}$) is specified in one normative document (VPAM APR 2006 "General basis for ballistic material, construction and product tests - Requirements, test levels and test procedures"). Moreover, the backface signature deformation profile (P-BFS) is determined only in tests conducted according to two standards – the above-mentioned standard and in accordance with the HOSDB Body "Armour Standards for UK Police (2007) Part 2: Ballistic Resistance".

The range of the backface deformation assessments is presented in Table 2.

Plasticine or clay as a material for BFD measurement is proposed for all standards, although only four of them specify the manufacturer of the material and its plasticity characteristics. This is important from the point of view of the repeatability of the test results obtained.

In scientific research, in addition to plasticine and clay, gelatin [3-4], a phantom can imitate the human body form [5] or an animal model is used e.g., a cadaveric pig barrel was applied [6].

Most of the standards discussed indicate deformation at the level of 40–44 mm as acceptable, while only one of the standards requires the use of a statistical tool to estimate the percentage probability of deformation equal or lower than 44 mm (NIJ Standard 0101.06 "Ballistic Resistance of Body Armor"). The Gost 34286-2017 standard requires a deflection of no more than 17 mm, but only for small calibers.

Gott [7] discusses aspects of the selection of the method of ballistic testing of body shields, referring to the actual conditions of their use in the context of the diversity of ammunition for handguns and their alleged equivalence to each other, pointing out significant differences between the conditions of ballistic tests and real situations.

The dynamic changes in the pressure wave from a ballistic impact on a gelatin block was studied and compared with the projectile type applied [8]. The study's conclusion is that the waveform and twin peak of the transient pressure wave are independent of the projectile type, while the parameters of the pressure wave depend on the projectile. The above observations allow to gain new BABT risk knowledge and support for the projectile design process. Shaomin Luo, et. al [9] determined the transient effect of ballistic gelatin behind soft armor impacted by a handgun bullet (9 mm Parabellum). The study confirmed that the cavity expansion–contraction movement is self-similar and can be

Standard	Evaluation parameter			
	BFD (backface deformation)	$*V_{50}$	P-BFS (profile of deformation)	$V_{deformation}$ (volume of deformation
PN-V-87000:2011 „Light ballistic armors - bullet-and fragment-proof vests - requirements and tests”	✓	×	×	×
NIJ Standard 0101.04 „Ballistic Resistance of Body Armor”	✓	✓	×	×
NIJ Standard 0101.06 „Ballistic Resistance of Body Armor”	✓	✓	×	×
VPAM BSW 2006 „Personal Protective Equipment Ballistic Protective Vests - Requirements, Classifications and Testing Methods”	✓	×	×	×
VPAM APR 2006 „General basis for ballistic material, construction and product tests - Requirements, test levels and test procedures”	✓	✓	✓	✓
HOSDB Body „Armour Standards for UK Police (2007) Part 2: Ballistic Resistance”	✓	✓	✓	×
Gost 34286-2017 „ARMORED CLOTHING. Classification and general Specification”	✓	×	×	×

Table 1. Classification of standards in the area of personal ballistic protections

Standard	BFD		
	Backing material	***Maximum permissible depth***	***Method of assessment***
PN-V-87000:2011 „Light ballistic armors - bullet- and fragment-proof vests - requirements and tests”	Plastic material (clay, plasticine). Material plasticity 25.0 ± 3.0 mm	≤ 40 mm	Depth measurement (BFD) ≤ 40 mm for all velocity tested. No statistical tool for the assessment
NIJ Standard 0101.04 „Ballistic Resistance of Body Armor”	Roma Plastilina No. 1. Material plasticity 20.0 ± 2.0 mm	≤ 44 mm	FAIL/PASS (CP/PP) Criterion. BFD measurement for shot 1 for the required velocity. The remaining BFD shall be recorded for higher velocity at shouting points 2 and 3
NIJ Standard 0101.06 „Ballistic Resistance of Body Armor”	Roma Plastilina No.1. Material plasticity 19.0 ± 2.0 mm	≤ 44 mm	FAIL/PASS (CP/PP) Criterion. BFD measurement for shots 1, 2 & 3 for the required velocity. Average value for all BFD taking into account the factor k_1. $Y_U=Y+k_1s$ Probability that 80 % of the BFD measurements for the sample are ≤ 44 mm at 95 % confidence level $Y_U=Y+k_1s$
VPAM APR 2006 „General basis for ballistic material, construction and product tests - Requirements, test levels and test procedures”	Plastic material (plasticine). Material plasticity 20.0 ± 2.0 mm	≤ 40-44 mm (depending on the plasticity of the substrate)	Limit of the indentation depth in plasticine is determined by the plasticity of the plasticine 20.0 ± 2.0 mm. The sum of the average value of the plasticine measurement and the constant of 22.0 mm (medical constant), from which the maximum allowable indentation depth is derived.
HOSDB Body „Armour Standards for UK Police (2007) Part 2: Ballistic Resistance”	Roma Plastilina No.1 (unformed armour) Material plasticity 19.0 ± 2.0 mm	≤ 44 mm (single shot BFS limit -handguns) ≤ 25 mm (max. mean BFS – rifle, shotgun)	Depth measurement (BFS) for all velocity values. Assessment of the shape of the deformation (hemispherical/pencilling)
	Plastiline® 40 (formed armour) Material plasticity 7.0 ± 2.0 mm	The BFS is not assessed in formed armour testing	Held or perforated. Assessment of the shape of the deformation (hemispherical/pencilling)
Gost 34286-2017 „Armored clothing. Classification and general Specification”	Plastic material (plasticine)	≤ 17 mm	Depth measurement for handguns only

**PP/CP – Partial Penetration/Complete Penetration*

Table 2. Summary of standards considering the BFD criterion in a particular test material

approximated to semi-ellipse. In [10] characteristics of the temporary cavity effect were investigated using a soft body vest made of UHMWPE fibres and a 9 mm Luger bullet. The main finding from the research is the conclusion that the maximum depth deformation rose in the quadratic function of the velocity. Struszczyk et. al [11] studied the effect of PACVD (Plasma Assisted Chemical Vapour Deposition) surface modification UHMWPE fibrous composites and para-aramid fabrics with the deposition of a fluoro- or silane-like-polymer on the propagation of the pressure wave resulting from a bullet (7.62 mm FMJ Tokariev m = 5.5 ± 0.1 g). The wave performance was related to the type of textiles in the ballistic system. The modification positively influenced the stability of ballistic properties and decreased the risk of the BABT.

Kumar et. al [12] and Thornby et. al [13] indicated the variation of the ballistic behavior of bullets made by various manufacturers especially with respect to asymmetric thinning of the jacket in regions of pre-impact weakness. The bullets were analyzed via CT, subsequently impacted into a rigid flat plate, and the resulting bullet deformation was re-analyzed [12].

Therefore, when testing ballistic products for safety, it is essential to verify that a bullet's source has an effect on how energy travels through a shielding made from different materials. The research thesis assumed that the projectiles' origin (including differences in the jacket chemical composition and manufacturer) used to assess ballistic application safety affects V50 parameters, bullet-proofness, and p-BFS levels, such as the deformation depth, surface area, and shape. The study aimed to determine the effect of the origin of the bullet on the safety test results for models of ballistic systems made from two types of textile materials differing in structure and manufacturing process: p-aramid unidirectional unwoven fabric and unidirectional unwoven fabric made of ultra-high molecular weight polyethylene fibers (soft fibrous composite).

2. Materials and Methods

2.1. Materials

Ballistics tests were carried out for two types of textile material samples with dimensions of at least 400 x 400mm: Barrday Barflex U590 (Barrday, USA; surface density: 249 ± 1 g/m^2, thickness: 0.23 ± 0.02 mm) and Dyneema® SB51 (DSM, The Netherlands;surface density: 256±1g/m2,thickness:0,29 ±0,02mm).

The system tested, Barrday Barflex U590, consisted in 14 layers of the ballistic materials, whereas the Dyneema® SB51 system had 12 layers. The areal density of the soft ballistic applications were as follow:

a) designed from Barrday Barflex U590 – 3486 g/m^2;
b) designed from Dyneema SB51 – 3072 g/m^2.

For the ballistics tests two 9 x 19 mm FMJ bullets of different manufacturer origins were applied (Figure 1):

- 9 mm FMJ/RN/SC (steel jacket), m = 8.0 g ± 0,1 g, type: DM41; manufacturer: RUAG;
- 9 mm FMJ/RN/SC (brass jacket), m = 8.0 g ± 0,1 g, manufacturer: WINCHESTER.

2.2. Methods

When developing a new design of ballistic materials, it is necessary to determine their ballistic resistance as described in the selected research methodology specified in available normative documents,such as the speed range V50 at which the probability of penetration of the shield is 50% and is defined for a specific material against a given threat (projectile type).

The bullet hit the test sample at an angle of incidence of 0°, the tolerance of which did not exceed the nominal value by more than ± 5°. Tests were conducted at ambient temperature (20 ± 3) °C, with relative air humidity (50 ± 20) %, within not more than 30 minutes from the moment of removal of the sample from the room where it was thermostated (>16 h).

The following devices were used for testing:

- bullet velocity measurement station (type: infrared photoelectric gate type: BP-02/speed meter VT-08; manufacturer: Institute of Mechanics and Construction Technical University of Warsaw/Poland);
- technical scaleweight (type: WPT 5 II; manufacturer: Precision Mechanics Facility RADWAG/Poland;
- thermohygrometer (type: JB-913R; manufacturer: Oregon Scientific/USA);
- caliper (manufacturer: FWP VIS/ Poland);
- depth gauge (manufacturer: FWP VIS/Poland);
- tape measure (type: M550; manufacturer: DEDRA/Poland);
- universal mount suitable for ballistic speed barrels with laser sight

(a) (b)

Fig. 1. 9 mm FMJ projectile used in study: (a) 9 mm DM41 (RUAG); (b) 9 m FMJ (WINCHESTER)

(UZ 2002; manufacturer: Prototypa s.r.o./Czech Republic);
- 9 mm velocity barrel (manufacturer: Prototypa s.r.o./Czech Republic)
- ballistic plasticine item No.071756 (manufacturer: Carl Weible KG)
- drop weight: steel sphere, size: 63.5 mm ± 0.05 mm in diameter, mass: 1.039 ± 5 g.

Plasticine was stored for at least 16 hours at a constant temperature (± 2 °C) to ensure a substrate plasticity of 20.0 ± 2.0 mm. To test the plasticity of the plasticine, a steel weight was used, dropping it from a height of 2000 ± 5 mm at least 5 times.

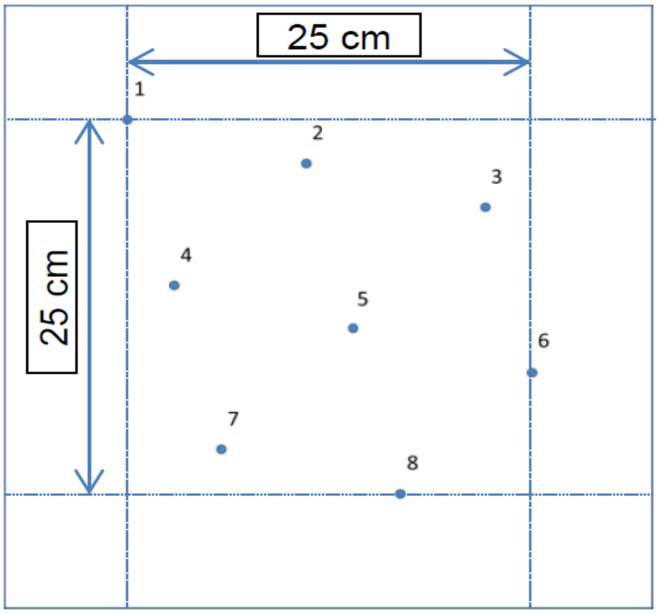


Fig. 2. Fixed sequence of shots for systems tested

2.2.1. V50 ballistic protection limit

A ballistic protection limit test was performed using of two types of 9 x 19 mm FMJ ammunition in a selected sequence of shots, max. 8 shots per sample. The dimensions of the samples were 400 × 400 mm. The sequence of shots was chosen to minimize the impact of previous shots on the result of subsequent shots (Figure 2).

If no V50 result was obtained for the first sample, the same procedure was continued for subsequent samples until an acceptable speed was obtained within the dispersion according to the methodology.

Calculation methodologies were used in accordance with the following:
- NATO STANAG 2920 Ed.2; [15]
- NATOSTANAG 2920 Ed.3 – AEP 2920 Edition A, Version 1; [16]
- NIJ Standard 0101.04 (Ballistic Limit); [17]
- VPAM Ballistic Standard APR 2006. [18]

2.2.2. Bullet-proofness

A bullet resistance test was performed in accordance with PN-V-87000:2011, with 8 shots fired at an angle of incidence of 0 ± 5° and in the speed range of 400 ± 15 m/s.

As part of the research, the number of partially penetrated (PP) layers of the sample and the depth, surface area and volume of the backface signature (BFS) were determined. In this study 8 shots were fired into the sample at an angle of 0 ± 5° (Figure 2).

For each impact of the projectile, the following factors were determined:

Vdps – volume of the BFS in clay determined from the formula:

$$Vdps = 2/3 \times \pi \times a \times b \times BFD\ [cm^3] \qquad (1)$$

where: *a, b - semi-axes of the ellipse [cm]; BFD - depth of backface deformation [cm]; Vdpw – volume of the BFS in clay determined using a burette with water;*

Pdpe – surface area of the BFS in clay for ellipse (for bullet impacts at an angle of 0 ± 5°) determined from the formula:

$$Pdpe = \pi \times a \times b\ [cm^2] \qquad (2)$$

Pdps - surface area of the BFS in clay (for bullet impacts at an angle of 0 ± 5°) determined by making an outline of the deformed area on tracing paper.

The tracing paper was cut into dimensions of 100 × 100 mm and weighted on analytical scale , and then its area was calculated using the weight method based on a standard curve.

Iw - the number of layers for which the penetration of the sample was recorded.

Reading of the deformation depth (BFD) was made using a depth gauge, and that of the length of the semi-axis of the ellipse was made using a caliper. The volume of backface signature deformation (Vdpw) was determined by a burette, used to accurately measure liquids of a certain volume. Water with the addition of a surface tension lowering agent was used to significantly improve the accuracy of the measurement. Values of the surface area and the volume of deformation were determined using the classical method using appropriate formulas.

The coefficients *Vdps/Vdpw, Pdpe/Pdps* were calculated, showing the degree of matching of the values obtained by various techniques. The *Pdps/Vdpw* coefficient was also determined.

2.2.3. Residual energy

According to VPAM APR 2006, the residual energy of the projectile transferred to the body must not exceed 70 J. The maximum permitted volume, measured in terms of the average value of the plasticity measurement, is approximated by the formula:

$$Vdef = F \cdot E = (0.134 \cdot BFD_{av} - 1.13) \cdot E \; [18] \quad (3)$$

where: *E - residual energy transferred to the user's body; F - proportionality coefficient between the maximum permissible deformation volume (Vdef) and the residual energy generated behind the ballistic protection, taking into account the value of the average depth of substrate deformation resulting from the dis-charge of the weight for a given plasticity of the plasticine;* BFD_{av} *– average depth value after the fall of a steel ball onto a plastic material (drop test).*

Factor F is calculated as a proportionality coefficient between the maximum permissible deformation volume (Vdef), the residual energy generated behind the ballistic protection, and the average depth value after the fall of a steel ball onto a plasticity material (drop test). Factor F can be easily determined as value y for the linear function relationship between the F-factor and average indentation depth. [18]

3. Results and Discussion

3.1. V50 ballistic protection limit

V50 tests for the model soft ballistic applications developed were performed to confirm the requirements for the V50 ballistic protection limit of the ballistic insert developed and to preliminary determine the effect of the bullet manufacture.

The V50 results for the Barrday Barflex U590 and Dyneema® SB51 systems using a 9 mm DM41 projectile are presented in Tables 3–4, and for a 9 mm FMJ WINCHESTER projectile - Tables 5–6.

The main conclusion of the abovementioned tests confirm that for the Barrday Barflex U590 ballistic system using the two types of bullets, the V50 parameter achieved a significantly higher value when the 9 mm FMJ WINCHESTER projectile was used in ballistic test (Tables 3 and 5).

With the 9 mm DM41 projectile, the V50 obtained for this system differed by about 20 m/s in tests where the 9 mm FMJ WINCHESTER projectile was used, regardless of the research methodology used. This difference was slightly lower only when applying the methodology from VPAM APR 2006.

A similar phenomenon was found when testing the Dyneema® SB51 ballistic system (Tables 4-6). The V50 level was even higher by about 30 m/s in tests where the 9 mm FMJ WINCHESTER

Methodology	V50 [m/s]	D	Number of shots
NATO STANAG 2920 Ed.2	431.4	24.0	6
NATO STANAG 2920 Ed.3 – AEP 2920 Edition A, Version 1	436.8	38.2	10
NIJ Standard 0101.04 (Ballistic Limit)	437.6	33.0	12
VPAM APR 2006	440.0	Not applicable	16

Table 3. V50 results for Barrday Barflex U590 system using a 9 mm DM41 projectile

Methodology	V50 [m/s]	D	Number of shots
NATO STANAG 2920 Ed.2	433.9	22.5	7
NATO STANAG 2920 Ed.3 – AEP 2920 Edition A, Version 1	434.7	24.8	11
NIJ Standard 0101.04 (Ballistic Limit)	436.5	18.3	12
VPAM APR 2006	438.2	Not applicable	22

Table 4. V50 results for Dyneema® SB51 system using a 9 mm DM41 projectile

Methodology	V50 [m/s]	D	Number of shots
NATO STANAG 2920 Ed.2	450.4	9.6	9
NATO STANAG 2920 Ed.3 – AEP 2920 Edition A, Version 1	455.8	17.0	23
NIJ Standard 0101.04 (Ballistic Limit)	456.1	17.0	24
VPAM APR 2006	456.3	Not applicable	24

Table 5. V50 results for Barrday Barflex U590 system using a 9 mm FMJ WINCHESTER projectile

Methodology	V50 [m/s]	D	Number of shots
NATO STANAG 2920 Ed.2	460.5	30.4	8
NATO STANAG 2920 Ed.3 – AEP 2920 Edition A, Version 1	460.9	35.1	11
NIJ Standard 0101.04 (Ballistic Limit)	459.2	34.5	12
VPAM APR 2006	461.8	Not applicable	24

Table 6. V50 results for Dyneema® SB51 system using a 9 mm FMJ WINCHESTER projectile

Ballistic System made of:	Bullet velocity [m/s]	Penetration [CP/PP]	Number of penetrated layers in ballistic system	BFD [mm]
Barrday Barrflex U590	400.7	PP	4	30.0
	400.5	PP	4	28.7
	397.5	PP	4	30.2
	398.6	PP	5	33.3
	400.3	PP	4	28.9
	405.0	PP	4	30.9
	397.4	PP	6	33.4
	401.0	PP	4	31.5
Average	400.1 ± 2.4	-	4.4 ± 0.7	30.9 ± 1.8
Dyneema SB51	400.3	PP	4	28.0
	401.3	PP	4	28.0
	399.4	PP	5	27.9
	399.0	PP	4	27.5
	399.2	PP	4	26.4
	399.4	PP	5	30.8
	397.4	PP	5	28.7
	401.1	PP	5	31.7
Average	399.6 ± 1.3	-	4.5 ± 0.5	28.6 ± 1.8

**PP/CP – Partial Penetration/Complete Penetration*

Table 7. Summary of bulletproof test results for Dyneema SB51 and Barrday Barrflex U590 soft ballistic systems using 9x19 FMJ DM41 ammunition

projectile was used, which significantly confirms the impact of the source of missile acquisition on the V50 parameter regardless of the type of ballistic system tested.

3.2. Bullet-proofness acc. to PN-V-87000: 2011 standard

The value of the backing material deformation depth (BFD) is one of the parameters determining the bullet resistance of ballistic inserts. According to PN-V-87000:2011, the depth of the deformation cannot be higher than 40 mm. Based on the calculated value of V50, it was assumed that the bullet resistance tests of the above-mentioned materials in accordance with PN-V-87000:2011 methodology should meet the requirements for 9 × 19 mm DM41 and 9 × 19 mm WINCHESTER ammunition (special class 400 ± 15 m/s).

Results of the bulletproof test for Dyneema SB51 and Barrday Barrflex U590 soft ballistic systems using 9x19 FMJ DM41 ammunition are presented in Table 7.

A bulletproof test summary for the Dyneema SB51 and Barrday Barrflex U590 soft ballistic systems using 9 × 19 FMJ WINCHESTER ammunition is presented in Table 8.

The Barrday Barrflex U590 ballistic system obtained a higher value of the BFD when the 9 mm FMJ DM41 projectile was used in the ballistic test (30.9 ± 1.8 mm), comparable with the test using the 9 mm FMJ WINCHESTER projectile (27.1 ± 1.5 mm). For the 9 mm FMJ WINCHESTER projectile, the number of shot layers for the Barrday Barrflex U590 are fewer than for the 9 mm FMJ DM41 projectile.

In the ballistic system designed with the Dyneema SB51, a similar phenomenon was found: for the 9 mm FMJ DM41 projectile test; the BFD achieved 28.6 ± 1.8 mm, which was significantly higher than for the test in which the 9 mm FMJ WINCHESTER projectile (26.0 ± 1.1 mm) was used. Moreover, it was also confirmed that the number of penetrated layers in the ballistic system was significantly higher when using the 9 mm FMJ DM41 projectile (4.5 ± 0.5) in comparison to the tests where the 9 mm FMJ WINCHESTER projectile (2.8 ± 0.7) was used.

The BFD and p-BFS (Pdp, Vdp) values for the two soft ballistic systems and using the two types of ammunition:: 9 × 19 FMJ DM41 and 9 × 19 FMJ WINCHESTER are shown in Tables 9–10.

The average value of the deformation volume (Vdps) increased when the 9 mm FMJ DM41 projectile was used in the ballistic test, whereas in the case of Vdpw, this parameter maintained a comparable value for both projectiles for the Barrday Barrflex U590 ballistic system. A comparable phenomenon occurs for Dyneema SB51 ballistic system. Higher values of the average area deformation (both Pdpe and Pdps) were found when the 9 mm FMJ DM41 projectile was applied for the ballistic verification of Barrday Barrflex U590 and Dyneema SB51 soft ballistic systems.

Not all deformations have a simple, spherical geometry, and the sharpness of the deformation shape cannot be easily assessed. Taking the above into account, Pdps/Vdpw deformation was calculated to quantify the effect of the strain shape on injury. However, the correlation is difficult to interpret when it is analyzed over the entire range of the depth of deformation, because this ratio decreases with the increasing size of the

Ballistic System made of:	Bullet velocity [m/s]	Penetration [CP/PP]	Number of penetrated layers in ballistic system	BFD [mm]
Barrday Barrflex U590	400.7	PP	*4*	26.9
	400.5	PP	*3*	27.3
	397.5	PP	*2*	26.0
	398.6	PP	*2*	24.8
	400.3	PP	*2*	26.0
	405.0	PP	*2*	28.6
	397.4	PP	*2*	27.5
	401.0	PP	*2*	29.4
Average	400.1 ± 2.4	-	2.4 ± 0.7	27.1 ± 1.5
Dyneema SB51	393.2	PP	3	27.1
	400.2	PP	3	26.3
	399.1	PP	2	25.5
	392.2	PP	2	24.5
	396.7	PP	3	24.5
	387.1	PP	3	26.4
	397.6	PP	4	26.1
	399.4	PP	2	27.3
Average	395.7 ± 4.5	-	2.8 ± 0.7	26.0 ± 1.1

**PP/CP – Partial Penetration/Complete Penetration*

Table 8. Summary of bulletproof test results for Dyneema SB51 and Barrday Barrflex U590 soft ballistic systems using 9 × 19 FMJ WINCHESTER ammunition

Ballistic System made of:	Deformation volume (Vdp) [cm³]		Deformation area (Pdp) [cm²]		BFD [mm]	Vdps/ Vdpw	Pdpe/ Pdps	Pdps/ Vdpw	E [J]
	Semi-sphere (Vdps)	Water measurement (Vdpw)	Ellipse (Pdpe)	Stroke (weight method) (Pdps)					
Barrday Barrflex U590	58.4	43.0	29.2	30.4	30.0	0.74	0.96	0.71	23.63
	45.3	30.0	23.7	24.2	28.7	0.66	0.98	0.81	16.48
	51.0	40.0	25.3	27.5	30.2	0.78	0.92	0.69	21.98
	57.4	35.0	25.9	27.4	33.3	0.61	0.94	0.78	19.23
	49.0	26.0	25.4	26.0	28.9	0.53	0.98	1.00	14.29
	59.0	37.0	28.7	28.0	30.9	0.63	1.02	0.76	20.33
	77.3	37.0	34.7	31.7	33.4	0.48	1.09	0.86	20.33
	57.3	37.0	27.3	28.8	31.4	0.65	0.95	0.78	20.33
Average	56.8 ± 9.7	35.6 ± 5.4	27.5 ± 3.4	28.00 ± 2.4	30.9 ± 1.8	0.63 ± 0.10	0.98 ± 0.05	0.80 ± 0.10	19.57 ± 2.97
Dyneema SB51	47.3	38.0	25.3	29.1	28.0	0.80	0.87	0.77	20.88
	53.6	32.0	28.7	26.5	28.0	0.60	1.08	0.83	17.58
	52.4	37.0	28.1	28.5	27.9	0.71	0.99	0.77	20.33
	45.9	30.0	25.0	28.5	27.5	0.65	0.88	0.95	16.48
	42.5	25.0	24.1	22.9	26.4	0.59	1.05	0.92	13.48
	63.7	35.0	31.0	29.6	30.8	0.55	1.05	0.85	19.23
	63.5	33.0	33.2	29.9	28.7	0.52	1.11	0.91	18.13
	61.7	39.0	29.2	28.2	31.7	0.63	1.04	0.72	21.43
Average	53.8 ± 8.4	33.6 ± 4.7	28.1 ± 3.1	27.9 ± 2.3	28.6 ± 1.8	0.63 ± 0.09	1.01 ± 0.09	0.84 ± 0.08	18.48 ± 2.56

Table 9. BFD and p-BFS values of the deformation of Dyneema SB51 and Barrday Barrflex U590 systems after testing using 9 × 19 FMJ DM41 ammunition

deformations (Pdps, Vdpw) regardless of their shape. Nevertheless, deformations with a sharper shape carry the risk of piercing more layers of material, which increases the risk of injury.

The average value of the residual energy was significantly higher for the tests where the 9 mm FMJ DM41 projectile was implemented (Barrday Barrflex – 19.57 ± 2.97 J; Dyneema SB51 – 18.48 ± 2.56 J), confirming the results obtained for the BFD and numbers of shot layers of the ballistic system. For the 9 mm FMJ WINCHESTER projectile, lower average BFD values were obtained

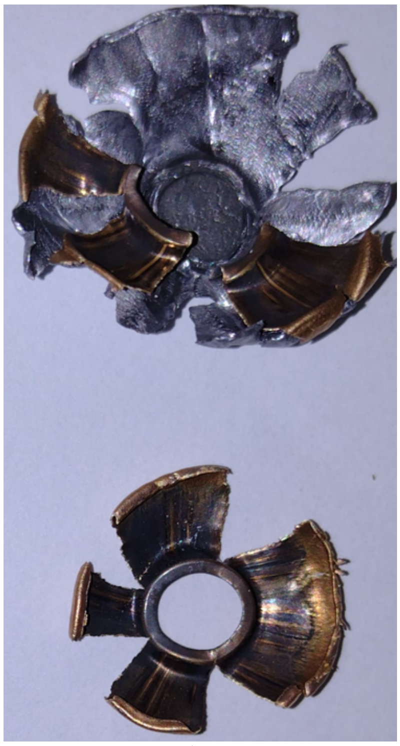
Ballistic System made of:	Deformation volume (Vdp) [cm³]		Deformation area (Pdp) [cm²]		BFD [mm]	Vdps/ Vdpw	Pdpe/ Pdps	Pdps/ Vdpw	E [J]
	Semi-sphere (Vdps)	Water measurement (Vdpw)	Ellipse (Pdpe)	Stroke (weight method) (Pdps)					
Barrday Barrflex U590	56.4	39.0	31.4	31.7	26.9	0.69	0.99	0.81	21.43
	43.0	28.0	23.6	23.9	27.3	0.65	0.99	0.85	15.38
	49.7	38.0	28.7	27.9	26.0	0.77	1.03	0.73	20.88
	33.7	28.0	20.4	20.1	24.8	0.83	1.01	0.72	15.38
	36.0	25.0	20.8	20.7	26.0	0.69	1.01	0.83	13.74
	60.3	39.0	31.7	26.9	28.6	0.65	1.18	0.69	21.43
	58.1	39.0	31.7	28.8	27.5	0.67	1.10	0.74	21.43
	62.1	37.0	31.7	27.1	29.4	0.60	1.17	0.73	20.33
Average	49.9 ± 11.1	34.1 ± 6.0	27.5 ± 5.1	25.9 ± 4.0	27.1 ± 1.5	0.69 ± 0.07	1.06 ± 0.08	0.76 ± 0.06	18.75 ± 3.30
Dyneema SB51	46.0	31.0	25.4	25.5	27.1	0.67	1.00	0.82	17.03
	47.9	34.0	27.3	26.8	26.3	0.71	1.02	0.79	18.68
	51.9	34.0	30.5	28.1	25.5	0.66	1.09	0.83	18.68
	43.0	28.0	26.4	24.6	24.5	0.65	1.07	0.88	15.38
	35.3	25.0	21.6	21.1	24.5	0.71	1.02	0.84	13.74
	48.1	33.0	27.3	25.3	26.4	0.69	1.08	0.77	18.13
	46.8	32.0	26.9	25.7	26.1	0.68	1.05	0.80	17.58
	50.5	33.0	27.8	25.1	27.3	0.65	1.11	0.76	18.13
Average	46.2 ± 5.2	31.3 ± 3.2	26.6 ± 2.5	25.3 ± 2.0	26.0 ± 1.1	0.68 ± 0.02	1.05 ± 0.04	0.81 ± 0.04	17.17 ± 1.76

Table 10. BFD and p-BFS values of the deformation for Dyneema SB51 and Barrday Barrflex U590 systems after testing using 9 × 19 FMJ WINCHESTER ammunition

than for the 9 mm FMJ DM41 projectile. The fact is that these bullets have a different jacket structure [Figure 4].

The average BFD values of the tested ballistic cartridges for the 9 mm FMJ DM41 projectile were in the range of 28.6–30.9 mm, and for the 9 mm FMJ WINCHESTER projectile 26.0–27.1 mm. It can be seen that lower values were obtained for the 9 mm FMJ WINCHESTER projectile. Deformation as it occurs in the backing material after non-penetrating shooting affects the risk of injury. Using only depth measurement in the area of contact with the body will not provide us with full information about the BABT effect. Deformation as it occurs in a plastic substrate after non-penetrating fire affects the risk of injury. For this reason, the study was carried out together with measurement of the surface area (Pdp) and volume (Vdp) of deformation, which were performed for both soft ballistic systems under study.

a



b

Fig. 4. 9 mm FMJ projectiles after ballistic test: (a) 9 mm DM41 (RUAG); (b) 9 mm FMJ (WINCHESTER)

For the same values of deformation depth (Hdp), different surface areas (Pdp) and deformation volumes (Vdp) can be obtained. It can be assumed that the shape of the deformation (Hdp, Pdp and Vdp) can affect the magnitude of the injury. The research also shows that the correlation between the depth of deformation and the surface and volume of substrate deformation for given material systems, such as depth and shape, can be used for a more thorough assessment of ballistic material, taking into account the BABT aspect. There is empirical evidence that deeper deformations are more likely to cause injury, but for similar depths, deformations of greater volume will be more harmful [14].

After analyzing the data on Hdp, Pdp and Vdp in Tables 7-10, it is clear that the 9 mm FMJ WINCHESTER projectile shell carries less energy than the 9 mm FMJ DM41 projectile. This was confirmed not only by the higher values of V50 and the smaller number of pierced layers of material, but also by the residual energy that was transferred to the plastic substrate.

4. Conclusions

In this research, an attempt was made to demonstrate the correlation between the source of the projectile and the depth, shape and volume of deformation in the plastic substrate. It has been shown that the source of the projectile determines the results of the V50 range and differentiates the value of energy transferred to the plastic substrate simulating the user's body. For the above reasons, in the quality tests of ballistic products, the most critical conditions and materials (the worst case) should be selected in order to minimize residual risk as much as possible. The use of projectiles of the same type, but from different manufacturers, raises a significant risk associated with lowering the rigor of the test and developing soft ballistic applications that will not have a significant level of ballistic resistance for safety. The developed procedure of synergistic studies of the area, depth and volume of deformation formed after non-penetrating torso shield shooting into a plastic substrate can be used as a tool for determining BABT, which shows how the projectile energy after a non-penetrating bullet shot acts on human tissue. Deformations with the same radius of curvature can have different geometries with potentially different injury hazards and probability. In addition, the geometry of the deformation may be irregular, thus the radius of curvature would not be the same along the lower surface of the deformation.

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