sciendo
International Conference KNOWLEDGE-BASED ORGANIZATION
Vol. XXXI No 3 2025

ASPECTS OF BALLISTIC PANELS MADE OF ENDUMAX XF33, TESTED AGAINST DIFFERENT PROJECTILES

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Abstract: *This paper presents an experimental study for hard plates made of Endumax XF33– a UHMWPE ultra high molecular weight polyethylene. There are tested two plates with 68 layers and 135 layers, respectively. The objective of this research was to test different ammunitions (9x19 mm parabellum FMJ lead core, .44 magnum SJSP, 7.62x39 FMJ, 7.62x51 FMJ), and to investigate how the obtained values of BFD are positioned in relation to the limit of 44 mm, mentioned in Ballistic Resistance of Personal Body Armor NIJ Standard–0101.07. The projectile 7.62x39 produced a closer BFD to 44 mm (43 mm). For this threat, the author recommendations are to have a larger statistical population resulted from more numerous hits and or to add layer to this initial plate of 135 layers of Endumax XF33.*

Keywords: ballistic protection, 9x19 mm parabellum FMJ lead core, .44 magnum SJSP, 7.62x39 FMJ, 7.62x51 FMJ, Endumax, BFD (backface deformation)

1. About Ultra High Molecular Weight Polyethylene in Ballistic Impact

Engineers have started to use high-performance polymeric fibers and foils for ballistic protection even from the moment the patents have got recognition, many of these inventions being first introduced in military applications, even if these fabrics and foils have also gained the market for other industrial applications (cut-proof gloves, high-quality fishing lines, large fishing nets, ropes, sail cloth, fire-fighter equipment [1]. Protective applications include flexible body armor, breastplates, helmets and panels for helicopters, cargo planes, hulls of ships, high-speed coast guard boats, and ground vehicles.

Hard plates are insertable ballistic components, designed to protect against high-risk, high-velocity threats, such as rifle rounds and armor-piercing projectiles, complementing soft body armor, which primarily resists handgun threats. These plates are typically inserted into carriers worn over the torso and, less commonly, integrated into limb or helmet systems.

Table 1 presents a succinct information of materials used for manufacturing hard plates for individual armor protection, based on literature [2-8]. Hybrid design solutions, using a combination of the mentioned materials could be a future trend [9].

DOI: 10.2478/kbo-2025-0089

Table 1: Materials of hard plates for ballistic protection

Material Type	Typical Density (g/cm^3)	Failure Mode	NIJ Level Support	Advantages	Disadvantages
Ceramic (Alumina)	3.95	Brittle fracture	III/IV	Affordable, good hardness	Heavy, brittle
Ceramic (SiC)	3.21	Brittle fracture	III/IV	Lighter, better performance	Expensive
Ceramic (B_4C)	2.52	Brittle fracture	IV	Very light, highest hardness	Very expensive, brittle
Polymeric Composite (UHMWPE)	0.93	Plastic deformation, fiber pull-out	III (multi-hit capable)	Lightweight, multi-hit, no shatter	Temperature sensitive, expensive
Aramid Composite	1.44	Fiber rupture, delamination	II/III (when used as backing)	Good energy absorption, flexible	Degrades in moisture, limited to lower levels
Metallic (Steel)	7.85	Plastic deformation	III	High durability, low cost	Heavy, risk of ricochet
Metal-Ceramic Hybrid	5.0	Mixed (brittle + plastic)	III+/IV	Balanced protection and durability	Expensive, heavier than pure ceramics

While traditional systems have relied on monolithic ceramic materials, often backed by aramid or ultra-high-molecular-weight polyethylene (UHMWPE) layers, recent developments have shifted attention toward fully polymeric and composite-based solutions for plates. These materials, including high-performance thermoplastic matrices reinforced with UHMWPE or aramid fibers, offer significant advantages in terms of weight reduction, multi-hit resilience, and improved durability under mechanical and environmental stress.

Comparatively, ceramic-faced armor systems achieve superior penetration resistance through brittle fracture mechanisms, but often suffer from post-impact degradation and higher areal density. Metallic-based or hybrid ceramic-metallic composites offer improved structural integrity and multi-hit performance, yet at the cost of increased weight and reduced wearer mobility. Polymeric composite systems, particularly those with functionally graded or layered architectures, are increasingly being optimized to meet or exceed NIJ Level III and IV protection levels, offering a compelling balance between ballistic efficacy and user ergonomics. This report focuses on the materials science, structural design, and performance benchmarking of hard armor plates with an emphasis on polymeric and composite innovations, alongside a comparative analysis with ceramic and metallic systems under standardized ballistic threat profiles.

2. Experimental Methodology

2.1. Materials for the Plates

In the past few years, polyethylene armor plates have gained popularity among military members, police forces, and private security agents, mainly because of their minimal weight, strong resistance, and lasting performance. These plates are considered some of the lightest rigid armor solutions on the market. Made from UHMWPE, they help prevent fatigue and allow unrestricted movement without lowering protection levels. For users who wear armor for extended periods, polyethylene significantly reduces discomfort, offering a more practical alternative to heavier steel-based protection [10].

Polyethylene armor is waterproof, being recommended for high-moisture areas, marine missions, or continued use without compromising integrity.

Certainly, selecting UHMWPE in a design of a ballistic plate implies a compromise between the above-mentioned advantages and shortcomings like heat sensitivity (softening at prolonged exposure above 82°C and melting at approx. 129°C), financial aspect (carries a greater cost than steel alternatives due to specialized production processes), increased thickness (lighter than ceramic and steel plates, these tend to be more substantial in thickness).

Endumax XF33 was produced by Teijin Aramid and it is laminated film of UHMWPE, with cross-ply orientation, having a surface density of 146 g/m^2. "With excellent energy absorption properties, tenacity and impact resistance, Endumax® offers effective and comfortable ballistic protection solutions with an outstanding cost-performance ratio" [11].

Table 2

Plate	Layers	Mass [kg]	Thickness [mm]
1	68	0.80	11.40
2	135	1.54	20.40

There were produced two plates with dimensions 260 mm x 300 mm, with 68 layers and 135 layers of Endumax (Table 2). Plate weight may range from 2.5 kg (for lightweight ceramic/ UHMWPE) to 4 kg or more (for steel or heavy ceramic). Usually, such a plate thickness is 12–25 mm, depending on materials and protection level.

Heat and pressing treatment is given in Figure 1. The pressure of 5 MPa was uniformly applied over the plate.

Figure 2 presents the structure of Endumax sheet, before heat-pressing treatment, at different magnifications. The parameters were set based on [12] and [13].

2.2. Test Method and Ammunition

There were used four projectile, their characteristics being given in Table 3.

The impact velocity was measured with a HPI B472 chronograph. The backing support was Roma Plastilina no.1, as recommended by [14]. The imprint in the ballistic plastiline was measured with a depth vernier calliper with an accuracy of ±0.1 mm. Environmental conditions were: temperature 21±5°C, relative humidity: 60%, atmospheric pressure: 760±15 mm Hg.

Table 3

Projectile type	Bullet	Bullet mass [g]	Use [NIJ 0101.07]	Kinetic energy [J], max/min
9x19 mm Parabellum/ Luger	FMJ, lead core	8	Level NIJ HG2	688.9/ 743.0
.44 Magnum	SJSP (Semi jacketed soft point)	15.55	JHP, level NIJ HG2	1313.3/ 1560.4
7.62x39	FMJ	8	Nivel NIJ RF1, NIJ RF2	1920.9/ 2085.1
7.62x51	FMJ	9.55	Nivel NIJ RF1, NIJ RF2	3297.4 3343.6

Kinetic energy [J], max/min, the maximum and minimum values, calculated with measured velocities (maximum value and minimum value, respectively)

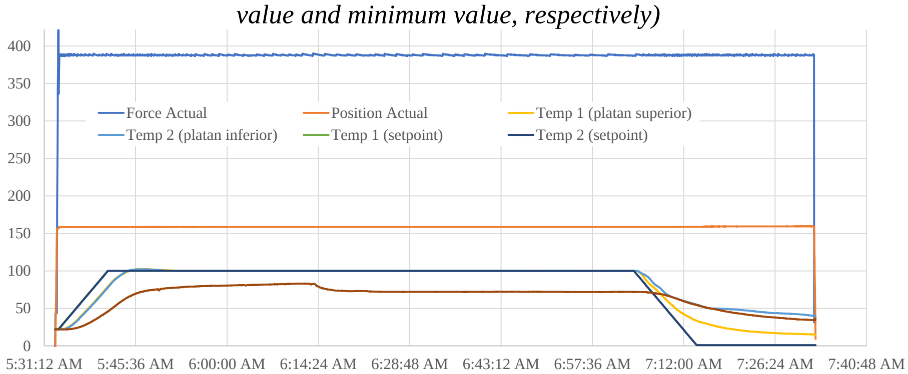
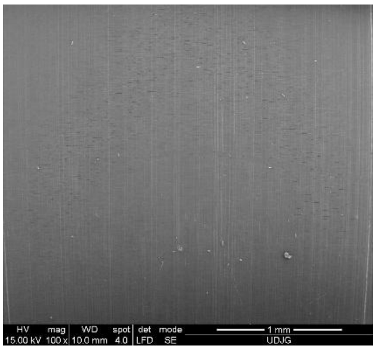
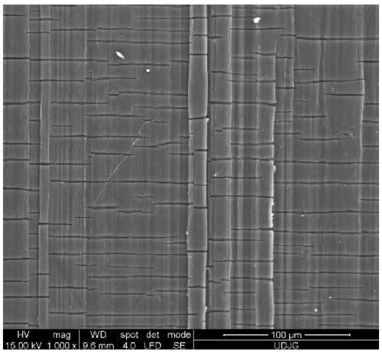


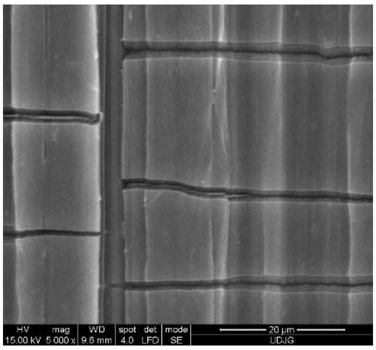
Figure 1: Compression force and temperature curves recorded during the hot pressing of the Endumax XF33 plate



a) ×100

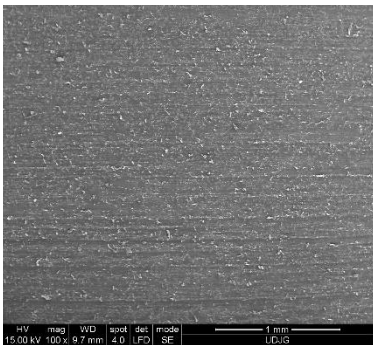


b) ×1,000

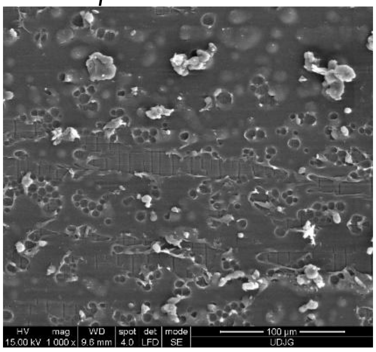


c) ×5,000

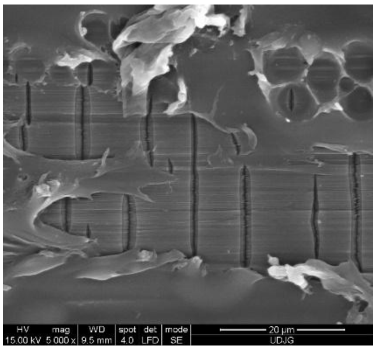
One side of the Endumax XF33 sheet



d) ×100



e) ×1,000



f) ×5,000

The other side of Endumax XF33 sheet

Figure 2: SEM images of Endumax XF33

3. Results on Testing Endumax Plates

Our study is in trend with recent developments focused on enhancing ballistic performance while reducing weight and improving comfort.

Tables 4 and 5 present the distance to the target, the ammunition and information about BFD.

The new standard introduced the term backface deformation BFD, instead of older BFD, with the following definition: the indentation in the backing material caused by a projectile impact on the test item during testing.

The average value for BFD, $\bar{Y}$, was calculated as

$$\bar{Y} = \frac{1}{N}\sum_{i=1}^{N} Y_i$$

where N is the number of hits and, consequently, the number of measured BFD and Y_i is the value of i-th measured BFD.

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(Y_i - \bar{Y})^2}$$

Calculated values are given in Tables 3 and 4. Multi-hit performance of a plate is not always guaranteed at higher protection levels. But experimental results point out a good behavior under multiple hits.

The plate made of 68 layers of Endumax XF 33 produced an average BFD of

- 19.25 mm for the projectile .44 Magnum SJSP, with a standard deviation of 2.20 mm (representing only 11.52% of this average value),
- 13.00 mm for the projectile 9x19 mm, FMJ, with a standard deviation of 2.45 mm (18.84% of the average value).

Of course, this evaluation is focused only on the plate's behavior under hits asks for a next step, test on the complete armor configuration, including both the flexible component and the plate.

Table 4. Results for the plate made of 68 layers of Endumax XF 33

Fire gun	Distance to target [mm]	Projectile	Hit number	Velocity (m/s)	Penetration	BFD (mm)	BFD_{ave} [mm]
.44 magnum ballistic barrel	5	.44 Magnum, SJSP	1	411	PP*	17	19.25
			2	441	PP	18	
			3	448	PP	22	
			4	442	PP	20	
9 mm ballistic barrel	5	9x19 mm, FMJ	1	422	PP*	13	13
			2	431	PP	16	
			3	415	PP	10	
			4	429	PP	13	

**PP – partial penetraction, SJSP – semi jacket soft point, FMJ – full metal jacket*

The plate made of 135 layers of Endumax XF 33 produced an average BFD of

- 33.67 mm for the projectile 7.62x51, FMJ, with a higher standard deviation of 8.14 mm (representing only 24.19% of average value),
- 20.75 mm for the projectile 7.62x39, FMJ, with a standard deviation of 7.72 mm (37.20% of the average value).

It is worthy to point out that for 7.62x51 FMJ, it was produced the deepest BFD (43 mm), too close to the limit of 44 mm [NIJ]. The difference among BFD on the same plate, under multiple hits is rarely discussed, but we think these reflects the capability of the plate to have closer response to this high-risk threat. Thus, for the lower velocity (and threat) projectiles, this difference was 4 mm for 44 Magnum, SJSP and 6 mm for 9x19 mm, FMJ. For the higher velocity projectiles, this difference is larger: 15 mm for 7.62x51 FMJ and 18 mm for 7.62x39, FMJ.

For a more accurate evaluation, statistical analysis should be performed for a larger number of hits as those presented in this study. The results obtaied for 7.62x51 FMJ suggests to test plates made of more than 135 layers of Endumax XF-33.

Figures 3 to 6 present high resolution macro photographs that point out the plate behavior under multiple hits.

For the thinner plate, .44 Magnum projectiles produce a back face deformation (BFD) over a larger area than those generated by the projectiles 9x19 mm.

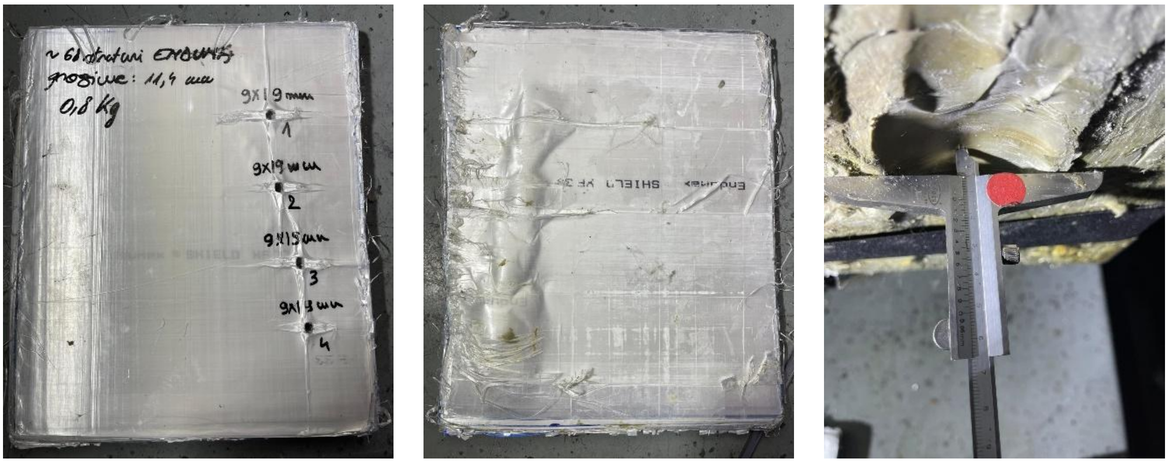
The high-velocity projectiles do not have a very waving effect on the plate face, but its back is severely formed, with visible delaminations of the last layers.

This qualitative analysis of the aspect of the face and back of the plates suggests that an investigation of the spatial appearance of the face and back should be investigated with the help of 3D measurements.

Table 5. Results for the plate made of 135 layers of Endumax XF33

Fire gun	Distance to target	Projectile	Hit number	Velocity (m/s)	Penetration	BFD (mm)	BFD_{ave} [mm]
Remington 700 rifle	15	7.62x51, FMJ	1	831	PP*	30	33.67
			2	833	PP	28	
			3	838	PP	43	
PM md.63 rifle	10	7.62x39 FMJ	1	693	PP	10	20.75
			2	701	PP	21	
			3	707	PP	24	
			4	722	PP	28	

**PP – partial penetraction, FMJ – full metal jacket*



a) b) c)

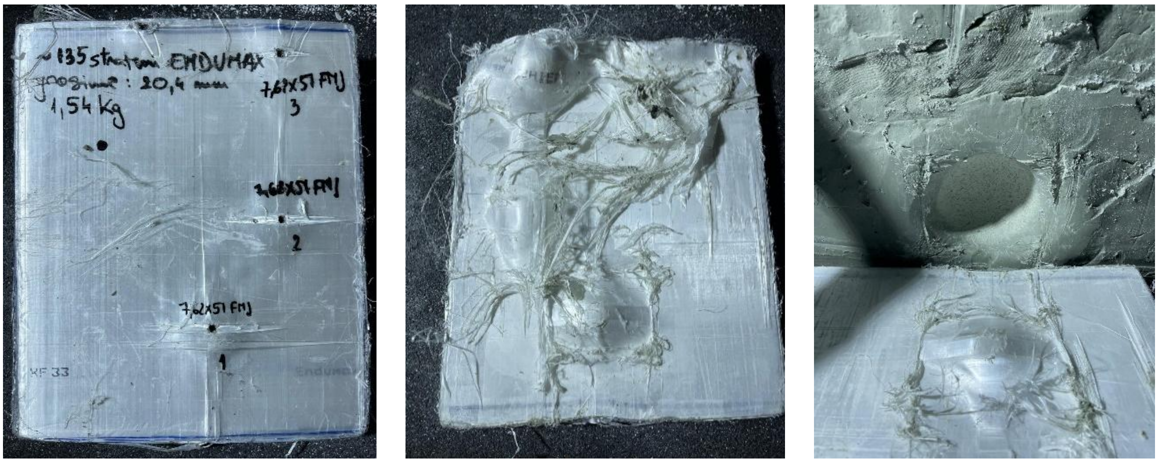
Figure 3: Plate with 68 layers of Endumax, tested with 9x19 ammunition:a) face, b) back, c) measurement of BFD for hit no. 4

a) b) c)

Figure 4: Plate with 68 layers of Endumax, tested with .44 ammunition: a) face, b) back, c) measurement of BFD for hit no. 1

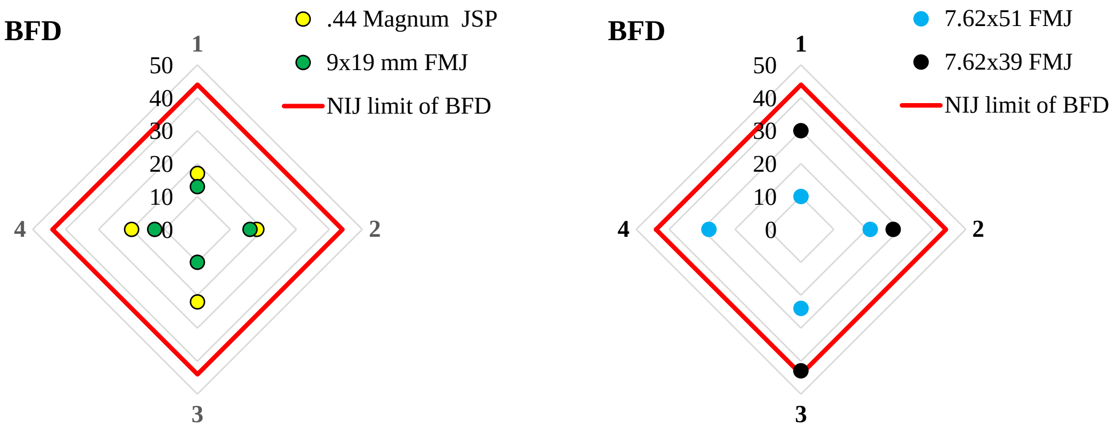
a) b) c)

Figure 5: Plate with 135 layers of Endumax, tested with 7.62x39 ammunition: a) face after hit no. 2, b) back after hit no. 2 and imprint in the ballistic support, c) measurement of BFD for hit no. 2



a) *b)* *c)*

Figure 6: Plate with 135 layers of Endumax, tested with 7.62x51 ammunition: a) face after 3 hits, b) back after hit no. 2 and imprint in the ballistic support, c) view of back deformation of the plate and the imprint in ballistic plastiline for hit no. 1



a) *b)*

Figure 7: Evaluation of BFD for the multiple hits: a) plate made of 68 layers of Endumax XF33, b) plate made of 135 layers of Endumax XF33

4. Conclusions

The objective of this research was to test different types of ammunitions on the two plate made of Endumax XF33 sheets and to investigate how the obtained BFDs are positioned in relation to the limit mentioned in Ballistic Resistance of Personal Body Armor NIJ Standard–0101.07 [14], a condition to be met by the tested samples is that each individual BFD measurement (BFD_i) ≤ 44.0 mm for the sample to be compliant. The low velocity ammunition positioned the BFDi much lower than that limit but high-velocity projectiles have two distinct behaviors. The projectile 7.62x51 FMJ produced a BFD smaller than 44 mm, but the projectile 7.62x39 produced a closer BFD to 44 mm (43 mm). For this threat, the author recommendations are to have a larger statistical population resulted from more numerous hits and or to add layer to this initial plate of 135 layers of Endumax XF33.

For a larger statistical population of data, the acceptance of the plate will be conditioned by meeting both conditions

$44.0 \text{ mm} \leq BFD_i \leq 50.0 \text{ mm}$

and

$BFD_{ave} + k_1 s \leq 44.0 \text{ mm}$

where BFD_{ave} is the average of all recorded fair hit BFD_i measurements, at maximum accuracy, for test objects of that exact model, dimensions, conditioning, and test threat, rounded to the nearest 0.1 mm [14]; s is the sample standard deviation and k_1 is an approximate factor that could be introduced for more than 12 hits on the same type of plate.

This approach can shorten the time for development of a hard frontal plate for individual protection.

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