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Plywood Panel with UHMW Polyethylene Board Ballistic Resistance

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Abstract

In this study, bullet-proof building panels are investigated. The aim of this work is to verify whether the polyethylene-plywood panels withstand frontal impact with high-speed projectiles. Ultra-high molecular weight polyethylene (UHMWPE) is a promising ballistic material due to its favorable properties – significant impact toughness and a high strength-to-weight ratio, meantime it is lightweight. By setting different parameters such as laminated plywood width and various UWHMPE facade layers, the protective effect of the panels and their performance characteristics are discussed using a 9 mm caliber handgun Glock 17 Luger bullets. The results show positive results – 3 of 4 combinations resist the bullet. The board with an arrangement of 2x32 cm laminated plywood outside and UHMWPE material inside the room captures 4 bullets; the bullets pass through the plywood layer and stop in the polyethylene. The experiment also tested individual UHMWPE panels at 2 different thicknesses to monitor the damage to the material. The results of this study will be useful in designing ballistic panels for buildings like unclassified buildings (army headquarters, safe rooms) from small arms weapons also for individual use.

Keywords: ballistic, composite panels, plywood, shooting range, UHMWPE.

Introduction

Ballistic defense continues to be one of the important areas for research and development in the civilian and military areas. Designing adequate protection for buildings and structures is complex due to the many technical requirements and factors that influence effectiveness. Regardless of life expectancy, a unique parameter in the construction of all military facilities is the specifications related to the building's force protection – the structure's inherent ability to provide safety and security and customary conditions to the occupants and equipment inside. (Borodinecs et al., 2019, 2022; Sanborn, 2018) Therefore, for relatively impact fragile civil buildings, wall reinforcement is significant. Traditional explosion-proof walls usually use high-strength concrete or are equipped with many steel bars to achieve wall reinforcement. This method is complicated by high-cost construction and increases the structure's weight. More importantly, it takes time to repair. (Wu et al., 2021) For this reason, this paper proposes relatively light ultra-high molecular weight polyethylene UHMWPE material connected with laminated plywood. Plywood combined with polyethylene is not yet widely used as a composite material, leading to scientific interest in using new materials but available in the market for ballistic defense.

There are many studies regarding UHMWPE material and its response to ballistic effects. Still, most of these studies are for body armor, not building materials. Applying prefabricated building modules significantly reduces on-site installation time and allows correct material specification and energy simulation due to precise measurements. (Borodinecs et al., 2017, 2019, 2020, 2022)

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The performance of UHMWPE in combination with plywood has not been investigated so far. The authors tested plywood for ballistic resistance (Barone et al., 2022). Both theoretical and experimental results showed that 3x28 mm plywood retained the bullet to a penetration depth of 64 mm and was the only bulletproof material compared to building materials such as spruce CLT or pine logs. Therefore, plywood was used as the UHMWPE layer variation in this experiment. Even though ballistic testing of CLT indicates that the material's inherent penetration resistance is significantly more excellent than lumber and plywood that are commonly used in temporary military structures. (Sanborn, 2018; Sanborn et al., 2019) Currently, wood is not assessed for the design of a protective system beyond use as a pre-detonation screen because of its low strength compared to steel and concrete. (Sanborn, 2018).

The general UHMWPE production process involves the fiber manufacture in a high-temperature gel-spinning process and then coated in resin, stacked crosswise to the desired thickness, and hot pressed. (Sanborn, 2018; van Dingenen, 1989) As commercially, the UHMWPE board is one of the most promising materials, researchers develop design and synthesis methods and specify the requirements for protection levels and zones. UHMWPE is a suitable material not only for light armor applications where high-velocity impacts are predominant (Carrillo et al., 2011a; Crouch, 2021; Firouzi et al., 2022). The research on UHMWPE in composites has mainly been focused on anti-shrapnel penetration, and there is little research on its anti-blast performance. (Wu et al., 2021) Wu X. et al. researched UHMWPE-based material and found that there should be a certain distance between the protective plate and the wall to be protected in the actual situation. And they dispute the fire safety of this material. (Ur Rehman et al., 2021; Wu et al., 2021) UHMWPE has properties such as low water absorption. The material is non-toxic, odorless, has good thermal insulation properties, has a simple chemical composition and structure, is chemically and radiatively neutral, has a low coefficient of friction and resistance to abrasion and wear, and has a significant impact on toughness (Wood W, 2012). It has a low density (930–950 kg/m^3), and it is lightweight (Karmakar, 2022), which makes it the best material in terms of a high strength-to-weight ratio (Karmakar, 2022; Wood W, 2012). UHMWPE material has high energy dissipation capability due to the large deformation. Due to its excellent impact resistance and low enough density, UHMWPE fiber has broad application potential in ballistic protection and material weight reduction. (Cao et al., 2021) UHMWPE fiber name is Dyneema SK60/Cuben Fiber is at present the strongest synthetic fiber in the world, being 10 times stronger than steel and 50% stronger than aramid fiber (tensile strength of 2.7 GPa). (Dyneema® Composite Fabrics (DCF) and Cuben Fiber Explained | Hyperlite Mountain Gear, n.d.; van Dingenen, 1989) However, compression and shear modulus will often be limited when using only Dyneema fibers in a composite. (Van Dingenen, 1989) UHMWPE has shown higher energy absorption capacity at higher impact velocities than at lower velocities. (Sanborn, 2018).

The material used in the study is PE1000. It has a molecular weight of 5–9·10^6 g/mol, is tear- and impact resistant, and remains flexible even at low temperatures – operating temperatures from – 250 °C to +80 °C. It is noise-absorbing and a suitable dielectric. However, UHMWPE is poorly used in the construction sector. Polyethylene cannot be glued together, so mechanical joining or welding (only for certain types) must be used. (E-Plastena.Lv/Polietilēns, n.d.) There are studies on the replacement of pile cushions with UHMWPE (Tulatorn et al., 2015), UHMWPE beam study (Attwood et al., 2016), and low-speed testing of UHMWPE beams (Karthikeyan et al., 2013). K. Sanborn comments that UHMWPE itself lacks the overall strength and stiffness for use as a structural panel (Sanborn, 2018).

The UHMWPE–plywood building panels are intended to be used alone or in combination for protection against small caliber and standard caliber projectiles or blast splinters, protecting against direct or accidental shots. Cao et al. have studied that for a 20 mm UHMWPE laminate, the penetration depth is approximately more than half the thickness of the laminate, and the back face deformation and delamination are significant (Karmakar, 2022). Several investigations (Koene et al., 2013; Koene & Broekhuis, 2017, 2019) have argued about the penetration into wood-based materials and wood.

Authors developed non-load-bearing panels for the walls of the buildings, made using prefabricated press-formed UHMWPE in varying configurations with birch plywood. Its thickness and brand were chosen because it is relatively commonly used but at the same time thick enough and of high strength/hardness to predict the retention of a 9 mm caliber bullet. Also (Sanborn, 2018) selected 1 inch (2.54 cm) thick UHMWPE in the experiments. As well as they could act as a "net" within the composite, deforming and perforating and providing significant energy loss to the projectile by dissipating its energy over a larger area and thus reducing its ability to penetrate (Sanborn, 2018) UHMWPE combined with CLT material lacks the overall strength and stiffness for use as a structural panel. The negative aspect is that UHMWPE material is expensive compared to other bulletproof materials such as fiberglass, metal plates, etc. (Sanborn, 2018) The numerical outcomes reveal the hybridization and distinctive stacking sequence of hybrid composites show a critical response to the ballistic performance. The outcomes additionally show that energy absorption capacity and ballistic limit velocity are delicate to projectile nose shape. (Karthick & Ramajeyathilagam, 2022).

The aim of this work is to verify whether the polyethylene-plywood panels withstand ballistic loads using 9 mm caliber Glock 17 Luger bullets. Both material coefficients of thermal expansion are not close – for UHMWPE, it is $\alpha=2\cdot10^{-6}$ K (Rama Sreekanth & Kanagaraj, 2014), but for plywood (temperature 20 °C and 65% relative humidity) $\alpha=28–31\cdot10^{-6}$ K.

Methods

The authors designed non-load-bearing walls of the buildings, made using UHMWPE in different configurations of press-formed panels with birch plywood. The experiment occurred under controlled conditions at the Riga shooting range. The air temperature during the experiment ranged from +5.1...+7.0 °C (January), and the relative humidity ranged from 65...70% (measured over 2 hours). A semi-professional shooter fired the bullets, thus bringing the situation closer to reality.

Due to the limited test conditions, EN1522/23 requirements were not completed, such as:

- A count of specimens – a minimum of 3 specimens are required for each design variant.
- The foil shot indication plate was not used.
- The room temperature must be not less than 12.7 °C to qualify for the official ballistic rating of the polyethylene-plywood panels designed.

The material damage results are described in the research work based on photographic recordings during the experiments. Possible material damage and ballistic resistance of the panel, depending on the material of the panel façade, were considered.

Sample panels were prepared from UHMWPE 150 mm wide and 20 mm thick and laminated plywood 32 mm (1 mm of each side is the lamination) thick with dimensions 500x500 mm. They were mechanically fastened using SPEC 17 galvanized yellow screws Ø 6 mm to a specially prepared wooden support (1000 mm high, 1500 mm wide) to test the material sample resistance to a fire 9 mm lead bullet. (Table 1) Plywood samples were made from LF-CPR/CE-DoP-01 – Riga® birch plywood (AS Latvijas Finieris) with a laminated surface coating, glued with phenolic formaldehyde glue, EXT glue quality, service class 2. Harmonized technical specification with EN 13986+A1:2015. The research limit was to use UHMWPE material in only one layer because the UHMWPE material is not the most cost-effective (Table 1). The future projections are to use recycled UHMWPE material, thus reducing panel costs and increasing sustainability.

Table 1

The econometric indicators of the materials used (prices August 02, 2022)

Material	Thickness (mm)	Density (kgm^{-3})	Weight (kgm^{-2})	Price (€m^{-2})
UHMW PE1000 (white)	20	930	23.25	310.29
UHMW PE1000 (green)	25	930	18.60	256.29
Plywood 32 mm	32	670	21.44	26.06
Plywood 2x32 mm	64	670	42.88	52.12

By EN1522/23 and EN1063, a 9 mm Luger cartridge for all tests was used. The experimental bullet was a standard 9 mm full metal copper jacket with 9 mm, 9x19 mm "Parabellum-Luger" ammunition with a weight of 8 grams. This cartridge type is used in tests where the structure or material to be tested (certified) has a declared ballistic resistance of FB2/BR2. The designed plate shall have the characteristic of preventing projectiles from penetrating at least 9 mm caliber cartridges. The Glock 17 pistol was used in the experiment. It belongs to the Austrian company GLOCK GmbH GLOCK series pistols. The Glock 17 pistol is chambered for 9 mm Luger cartridges. The specimen is mounted on a frame to reduce relaxation on impact, avoiding any indirect absorption of the energy generated by the shot by the mechanisms. The samples were tested without back support (Carrillo et al., 2011a).

According to standard EN 1063, there are expected to have three shots for each specimen. Thus similarly, in this experiment, 2-4 attempts were made. The number of shots to each sample was chosen based on the expectations of the highest resistance as No. 1_2 was the flattest and most economical material; thus 4 shots were fired. That was the only exception, as 2 shots were taken on the other specimen.

The specimens were tested at the impact velocity of 330 m/s, a 10-meter distance to the target, with a steel projectile considered to be non-deformable, with a diameter of 9 mm and a mass of 8 grams. Based on the calculations made with these data, the impact energy or energy used to assess the damage caused by the projectile was calculated. This energy was calculated using equation (Eq.1)

$$W_{kin} = \frac{m \cdot v^2}{2} = \frac{0{,}008 \cdot 330^2}{2} = 435.6 \text{ J} \quad (1)$$

E, J – is the kinetic energy of the projectile, m, kg – the mass, and v, ms^{-1} – the velocity of the shot.

The energy is obtained using these values as the projectile's energy that hits the sample. When the projectile manages to pass through the objective and residual velocity/energy is zero, as there is no perforation. (Carlucci & Jacobson, 2018; Carrillo et al., 2011b; Sanborn, 2018).

Experimental Part

This research is limited to the following:

- Glock 17 arm weapon with a bullet velocity of 400 m/s.
- Bullet's ogive-shaped nose.
- Random angle focusing on the perfect outcome, like a 90° angle between the bullet and a surface.
- The shooting range temperature is +6–7 °C in January.
- Two materials were used– plywood and UHMWPE.

First, the experiment tested individual UHMWPE panels and laminated plywood material to monitor the ballistic damage. Four different material samples were tested in the first part:

- Material sample No.1 is a 32 mm thick birch plywood board “Riga” with surface coating.
- Material sample No. 2 is a 32 mm thick birch plywood board “Riga” with surface coating – 2 layers, mechanically joined with four SPEC 17 metal screws Ø6 mm. Total thickness 64 mm.
- Material sample No. 3: UHMW PE1000, white – thickness 20 mm.
- Material sample No. 4: UHMW PE1000, green – thickness 25 mm.

Second, the experiments were about UHMWPE in different configurations with plywood.

Plywood and polyethylene boards separately. The samples were tested with a Glock 17 pistol and a 9 mm Luger cartridge. Shots were fired from a 10 m distance. The air temperature at the shooting range at the time was +7 °C, with a relative humidity of 65 %. First, sample No 1 (see Fig. 1 and Fig. 2) was tested. The plywood material did not stop the bullet as it was predicted.

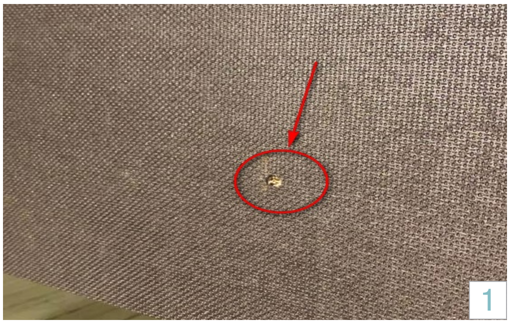

Fig. 1
Sample No.1, 32 mm thick birch plywood “Riga” front face after firing

Fig. 2
Sample No.1, 32 mm thick birch plywood “Riga” back face after firing

Sample No.2: 32 mm thick birch plywood “Riga” (with surface coating) - 2 layers, mechanically joined with four screws. Total thickness 64 mm. See Fig. 3 and Fig. 4. Two shots were fired with a Glock 17 pistol. Also, double plywood did not stop the bullets.

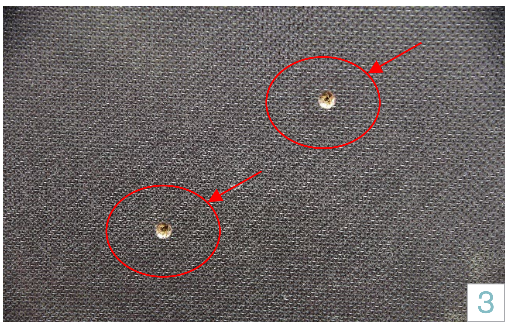

Fig. 3
Sample No.2 birch plywood “Riga” 2x32mm front face after firing

Fig. 4
Sample No.2 birch plywood “Riga” 2x32mm back face after firing

The third and fourth materials - UHMWPE sheets 150 mm wide, 20 mm, and 25 mm thick, UHMW PE1000 white and green color, respectively were tested next. Shots were fired from 10 m. The air temperature at the shooting range at the time was +7 °C, with a relative humidity of 70 %. Shots were fired with a Glock 17 pistol, using 9x19 mm Luger cartridges. UHMWPE stopped no bullets in samples 3 and 4. See Fig. 5 and Fig. 6.

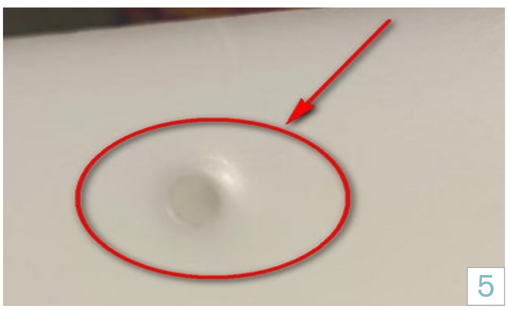

Fig. 5
Sample No.3 UHMW PE1000, 150 mm wide board, thickness 20 mm, white

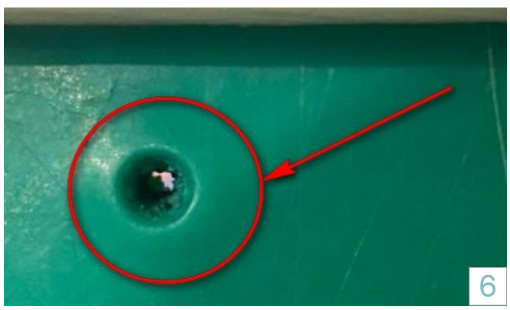

Fig. 6
Sample No.4 UHMW PE1000, 150 mm wide board, thickness 25 mm, green

Plywood-polyethylene boards. Materials separately did not stop the bullet; thus, the second part of the experiment was to verify if the combination of the prior two materials was successful. Therefore, the authors designed load-bearing and non-load-bearing panels for the walls of the buildings, made using UHMWPE in different configurations of press-formed panels with birch plywood. The combinations are also seen in Table 2.

Table 2

Bullet resistance of polyethylene – plywood panels

Panel No.	Panel position		Projectile	Penetrated	The material bullet stopped in	Experimental penetration depth, mm
1_1	front	20 mm UHMWPE	9mm Luger	yes	-	>53
	back	32 mm Plywood				
1_2	front	32 mm Plywood		no	UHMWPE	53 ± 1
	back	20 mm UHMWPE				
2_1	front	20 mm UHMWPE		no	plywood, 2^{nd} board	61 ± 1
	back	2x32 mm Plywood				
2_2	front	2x32 mm Plywood		no	UHMWPE	74 ± 1
	back	20 mm UHMWPE				

Panel No. 1_1. UHMWPE 20 mm – plywood 32 mm did not stop the bullet from Glock 17 pistol. The polyethylene layer was shot through, and the bullet penetrated the plywood. The plywood has delaminated 11 cross-laminated birch plywood sheets (1.45 mm thick each) in the adhesive layer (Fig. 7, Fig. 8), which have damage in the third wood veneer layer (not in the adhesive layer). The material did not stop all two control bullets.

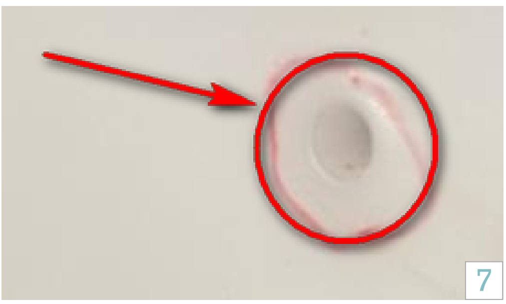

Fig. 7

Plate 1_1.UHMWPE 20 mm – plywood 32 mm front face

Fig. 8

Plate 1_1. UHMWPE 20 mm – plywood 32 mm side face

Panel No. 1_2. Sample 1_2 consists of 32 mm plywood followed by UHMWPE 20 mm as the second layer. The handgun fired four shots. The plate stopped the bullet on the first shot (Fig. 9). The bullets penetrated plywood, but the UHMWPE stopped the bullet. Local deformations in the polyethylene were found, coinciding with the bullet's trajectory. After the sample panel was extruded (Fig. 10), a deposit at the extrusion mid-point was found, presumably due to rapid internal tem-

Fig. 9

Plate 1_2.

Plywood – UHMWPE

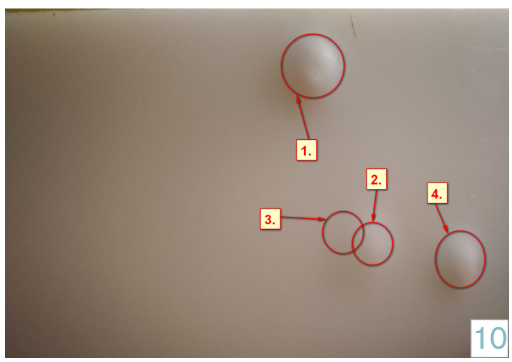

Fig. 10

Plate 1_2.

Plywood 32 mm – UHMWPE 20 mm after firing perature fluctuations. Since UHMWPE material has a melting point of 130 °C, a short-term impact at this temperature will not cause permanent deformation. The shooter performed three more control shots. All bullets were intercepted, including No.2 and No.3, fired closely and stuck in the same channel. No deformation increase in the polyethylene facade was detected when bullet No.3 struck bullet No.2. Possibly, the energy of the fired bullet was partially transferred to the existing channel of bullet No.2. The temperature rose; however, the energy was not sufficient for the proceeding of deformation. The maximum experimental penetration depth was measured as 53 mm.

Sample 2_1 consists of UHMWPE 1000 – 1 layer and 32 mm thick birch plywood "Riga" (with surface coating) double. Total thickness 84 mm. (20 mm + 2x32 mm) (**Fig. 11**). The bullet embedded into the second plywood board. The experimental penetration depth was measured as 61 mm. It was seen that the bullet penetrated the polyethylene and plywood's first layer but was stuck in the second plywood layer. The ballistic experiment revealed that the arrangement of the polyethylene layer influences the ballistic response.

Sample 2_2 consists of 32 mm thick birch plywood "Riga" with two layers of surface coating and 20 mm UHMWPE. Total thickness 84 mm (2 x 32 mm + 20 mm) (**Fig. 12**) The plate retained the bullet. The bullet was shot through 2 layers of plywood and stopped in the polythene. The experimental penetration depth was measured as 74 mm. We detected no local deformation of the facade in the polyethylene.

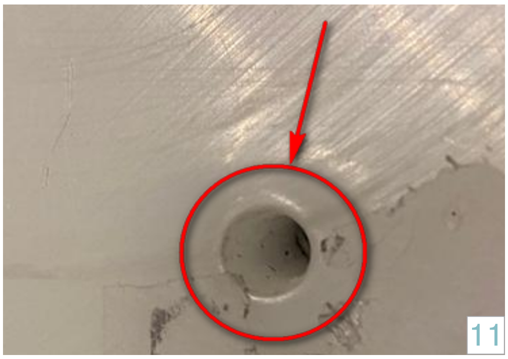

Fig. 11

Plate 2_1.

UHMWPE 20 mm – plywood 32 mm

Fig. 12

Plate 2_2.

Plywood 2x32 mm – UHMWPE 20 mm

Discussion

In the first part of the experiments, no sample of the plate material (without combining them) stopped the fired cartridge bullets. The observations showed that UHMWPE panels and plywood at 20 mm and 25 mm thickness alone are unsuitable for practical use in protection against small and standard caliber projectiles.

Fig. 13 shows that the UHMWPE board in the front and the plywood board in the second layer (1_1) do not stop the bullet. But if there are two plywood boards (2_1), the bullet stops in the second plywood board, making a 61 mm penetration depth (marked). The 1_2 variation of 32 mm plywood first and UHMWPE 20 cm second

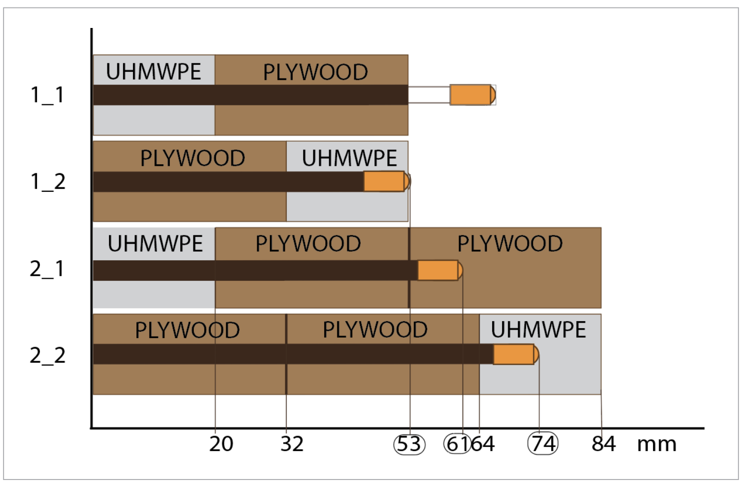

Fig. 13

The experimental penetration depth (mm) of the bullet for each plate combination made 61 mm terminal in a sample. But with 2x32 mm plywood, it is a 74 mm terminal. As this researched wall is a retrofitting wall, the thinnest wall is 52 mm of these boards to protect residents of the building.

The experimental penetration depth was measured manually using a steel bar with a diameter of 3 mm and a ruler with an accuracy of 1mm. (Fig. 14).

Fig. 14

Measurements of penetration depths

(a) (b) (c)

To compare the results with Sanborn, where the UHMWPE panel was mechanically affixed to the two CLT sections due to concerns with bonding the materials. This UHMWPE panel was one inch thick (25.4 mm) and placed between the 2-ply and 3-ply sections of CLT. Specimens with fiber-based ballistic panels also increased the ballistic resistance of the panel and were significantly lighter than the product with metal plates. (Sanborn et al., 2018) Fiber-based ballistic panels are expensive despite their excellent performance (Carrillo et al., 2011b).

The aim of this work is completed – the polyethylene-plywood panels in the right order withstand frontal impacts of high-speed projectiles using 9 mm caliber Glock 17 Luger bullets. The best sequence for the bullet resistance was 1x32mm plywood and UHMWPE as an inner layer. Bullets were embedded in polyethylene. UHMWPE's hardness combined with plywood is bullet impact resistant for the bullet's initial speed of up to 400 m/s. These boards can be bullet-proof walls (at least non-bearing).

The UHMW polyethylene begins to melt after receiving the initial load from the bullet. Melting means the kinetic energy is sufficient to heat the polyethylene to 130 °C.

Plate 1_2 consists of two 32 mm thick plywood layers outside mechanically bonded to a 20 mm thick UHMW polyethylene plate inside, which can qualify for ballistic resistance class FB2/BR2 to EN1063 and EN10522/10523. Birch plywood 32 mm thick absorbs the kinetic energy of a bullet to such an amount that the residual energy is insufficient to penetrate a 20 mm thick UHMW polyethylene sheet.

After the shot, it is possible to visually restore the panel with different options, like increased temperature by fusing the UHMWPE material). Still, it is unlikely that this repaired area would have the same level of protection against the next potential bullet. Alternatively, the hole/channels can be recessed/replaced with a stronger material (e.g., metal rod). This can be done immediately, so there are no open channels for an imminent attack (shot).

The next experiment would be varying the thicknesses of the plywood and UHMWPE boards (notably, the thickness of plywood could likely be reduced in tests 2_1 and 2_2) to make sure the minimal possible thickness is used for the maximum lightness of the wall, as well as in combination with other ballistic materials, like aramid fiberboard (Borodinecs et al., 2022).

Computer simulation would be considered for further study. These loads are not static and dynamic but high-velocity impact loads that make the simulation labor-intensive.

Conclusion

Ultra-high-molecular-weight polyethylene (UHMWPE) has many advantages, including ballistic protection, especially when combined with known materials such as laminated plywood.

In panels designed from several materials with different physical properties, each material's position (order) in the panel structure is essential. The material order can have a significant effect on the ability of the panel to resist ballistic loads. Various laminated plywood and UHMWPE specimens were tested for ballistic resistance. Separately they did not receive the ballistic limit, in contrast, specimen layers: plywood outside (at least 32 mm) – UHMWPE inside (20 mm) obtained relevant results than opposite order. Thus, it can achieve the qualification for ballistic resistance class FB2/BR2 to EN1063 and EN10522/10523. These panels can be a part of walls of various shelters like unclassified buildings, such as army headquarters, and safe rooms because of their relatively light density.

The polyethylene-plywood plates could be used in structures in the Arctic regions where temperatures are permanently low (down to -70°C). Because of the radio-impermeability property of polyethylene, the boards could be used both for the construction of residential Arctic complexes (screw piles, for instance) and for scientific structures, protecting with boards the radio-communication equipment that is essential for the development of the Arctic region and military applications as well. The Arctic region is considered the most promising region in terms of natural resources. As world history shows, most of the world's major armed conflicts occur in natural resource-rich regions; the use of panels will be appropriate to the risks involved.

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