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PROJECTILE PENETRATION DEPTH INTO WOOD-BASED FRAMES OF UNCLASSIFIED BUILDINGS

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Abstract

The study investigates the effects of projectiles on various wood-based frame panels for temporary unclassified buildings located in ballistically vulnerable locations (army headquarters, barracks, refugee shelters). The timber's ballistic resistance, particularly the penetration depth, was tested for pine log, flat birch plywood, and spruce cross-laminated timber (CLT) - specimens of different thicknesses. The Poncelet model is used for the theoretical calculus of penetration of the bullets, which is consistent with the experimental results. As a result of the experiment for the unclassified buildings, a panel of 84 mm plywood and a particular combined panel are suggested. None of the other materials – logs up to 190 mm, CLT up to 120 mm, and plywood less than 84 mm used in experiments are suggested. It was confirmed that selecting the test sample/ wall thicknesses should be based on theoretical calculations. In a further experiment - a combined panel of 60 mm CLT, 50 mm rock wool insulation, and 26 mm (and double 26 mm) plywood was generated and tested. The given panels have been chosen as the most applicable in the Nordic region. Such bullet-proof panel buildings are relatively quick and easy to assemble and repair and thus could be used for short-stay accommodation in non-standard vulnerable situations.

Keywords and phrases: bullet-proof, penetration depth, timber, unclassified buildings.
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1. Introduction

The world is unpredictable. Tomorrow, anyone may find themselves in a situation where private or social shelter from external threats, including weapon attacks, is vital to life. The topic of unclassified buildings with easy transfer and assembly, which can make a difference to a person's health, is particularly relevant. In this paper, structural timber frame buildings are analysed for people enduring short or long quarantine times to feel comfortable and protected from possible shooting attacks.

Timber frame buildings are ecological, energy-efficient, and economical. One of the possibilities is that wooden mobile temporary buildings would be convenient to place on the borders of troubled countries for groups of people, such as refugees. However, the security of these buildings from direct and stray bullets is critical. Unclassified buildings have been chosen as one of the directions, as part of them (military buildings, police buildings) are highly ballistically unprotected [1-4]. There has been no research, experiments, or an experience of unclassified wooden building ballistic response in the Nordic region. There are derogations (like the inhomogeneity) of the timber that affect its mechanical properties, including the projectile's performance. The behaviour of a bullet in timber is also unpredictable due to almost unpredictable knots of the timber that reduce the strength and endurance of wood [5-8].

Projectiles did not show deformation after penetration into Douglas, European pine, and European Oak targets [6]. The penetration depth of projectiles increases with impact velocity, and for softer wood, these parameters are close to linear dependence. Deflection of the projectile is related to the hardness of the target material and the direction of the wood grain [7, 9]. North America's Spruce-Pine-Fir and Southern Pine CLT bullet resistance for the military was studied to determine this. CLT thickness is required to stop a projectile based on striking velocity. For further experiments, enhanced CLT - with perforated steel plates, metal plates, aramid epoxy panels, mild steel plates, fiberglass sheets, and ultra-high-molecular-weight polyethylene plates was studied as a possible solution for the walls of temporary military structures [10, 13] as well as woven fabrics [14, 15] and composites [16-19]. Additionally, the various weather conditions, including CLT with higher moisture content, appeared to be unaffected in ballistic resistance, a promising characteristic for temporary military structures. [11] Research on CLT with an insulation layer to reduce CO_2 emission [20] and CLT properties overall [21] has been investigated. The penetration depths of bulleted wood material are related to the physical properties of wood [6, 22]. The action of the projectile in the material depends on the projectile velocity vi, m/s, ball mass mp, kg, wood moisture content W,%, wood density ρ, kg/m^3, wood hardness (Young's hardness, *N*), knotting, shear resistance τ, MPa, tensile stress σ, MPa. At the same time, the most important and relevant factors influencing penetrating capability are: (1) the mass of the projectile m_p, kg, the velocity at impact v, m/s, and the shape of the projectile head tip; (2) the characteristics of the target's resistance capability.

2. Materials and Methods

Wooden panels effectively stop the penetrating projectile by absorbing and dispersing its kinetic energy [23]. The experimental penetration depth data have been analysed using the Poncelet model (formula 1) derived from Newton's 2nd law of motion $F = m \cdot a$. The Poncelet model implies that the penetration resistance of wood can be addressed by several physically interpretable components [6, 11, 12, 24]

$$m_p \, dv/dt = F = -\beta - \alpha v^2, \tag{1}$$

where: m_p - the mass of the projectile, kg; v - velocity of the projectile at a given time t, m/s; β - a parameter dominated by the strength of the material, kg.m/s^2; α - represents the contribution of inertial stresses, kg/m; F - the force by which a projectile passes over a distance, N. It is important to simplify the calculation to a minimum and to assume that (1) the bullet does not deform at the moment of penetration. (2) the kinetic energy of the charge is used only for the deformation of the target. (3) among the many factors influencing the permeability, the main and significant ones are (a) the charge mass, the velocity at the moment of rebound, and the end shape of the charging head; (b) characterization of the target resistance capabilities. [22] Poncelet assumed that the penetrator is rigid with constant mass, so m = const. The penetration depth P of the projectile depends on the deceleration of the shot in the target and the projectile's velocity, as shown in equation (2)

$$P = m_p/2\alpha \cdot \ln(1 + \alpha v_1^2/\beta). \tag{2}$$

The integral of equation (1) gives the length P of the final penetration as the initial impact velocity (v_i). The parameters α and β [6] are determined experimentally from the penetration data. In this research, they are equated to similar material.

As the projectile passes through the material, its speed decreases but at the same time the material's resistance increases. The experiment tests the ballistic resistance (depth of penetration) of different wood types or wood products: A peeled pine log, commonly used in log houses, dried to 18% moisture content. Plywood samples were made from LF-CPR/CE-DoP-01 - Riga ® birch plywood (AS Latvijas Finieris) without a surface coating, glued with phenolic formaldehyde glue, EXT glue quality. Application in load-bearing building structures. The CLT material samples are locally produced at Cross Timber Systems, Jelgava (SIA Cross Timber Systems, 2021). Its moisture content is 12 ± 2%. Spruce, C24. The combined timber frame panel consists of 60 mm CLT, 50 mm rock wool isolation PAROC ROB 50 with specific thermal conductivity $\lambda_D = 0.037$ W/mK, and 26 mm (or +26 mm) plywood. These materials were chosen due to their high applicability in the Nordic region. The direction of the wood grain was not considered. In the first experiment, a Glock 17 handgun, and an APC556 firearm were used, which fired bullets into Pine log 110 mm and 190 mm thick, Birch plywood 28, 56, and 84 mm thick, and Spruce CLT 60, 80, 100, and 130 mm wide (Table 1). The Glock 17 and APC556 were also used to test the ballistic resistance of the composite panel in the second test.

Table 1. Weapons used according to the types of samples

	Weapons used (distance, speed)	**Glock 17**	**APC556**
	Sample types (thickness, mm)	**5m distance 400 m/s**	**10m distance 800 m/s**
A	Pine log	Pine log 110; 190 mm	Pine log 110; 190 mm
B	Birch plywood	Birch plywood 28; 56; 84 mm	Birch plywood 28; 56; 84 mm
C	Spruce CLT	Spruce CLT 60; 80; 100; 130 mm	Spruce CLT 60; 80; 100; 130 mm
D	Combined panel	Combined panel	Combined panel

Weapons regulations and ballistic protection standards must be followed [26-28]. The weapons used in the experiment represent the security levels FB2 and FB6 [27]. According to class FB2 and FB6, theoretical values - ball mass and speed - are taken because they were not measured in a shooting range but relied on the values of the technical sheet. Thus, the bullet velocity was 400 m/s for the Glock 17 revolver and 800 m/s for the APC556 automatic, with projectile weights of 8.0; 9.0 grams, respectively. The projectile with a shooting angle of 90° was fired from 5 and 10 meters. This distance depended on the weapon. Shooting distances of 5 and 10 meters are standard but do not necessarily equate to a real threat situation. If the shooting distance were increased, the wood would be more likely to withstand the force of the bullets.

3. Results

Experimental penetration depth

The experiment was organized at two shooting ranges in Riga city. The inner air temperature at both locations varied between +19°C and +21°C adapting to the outdoor summer temperature. The first experiment was a trial experiment - whether the timber would resist a bullet fired from 5- and 10-meters distance. The second experiment was based on the observations of the first shooting. The theoretical calculations were only carried out after the first shooting, which proved the experimental results. Each experiment was performed once. The shooting was human led; that is, the accuracy of the shooting depended on the success of the semi-professional shooter in depicting a real-life situation.

Log tests

First, dried pine logs (Figure 1) were placed in the shooting area, pre-connected vertically with $5 \times 200\,\text{mm}$ screws to replicate traditional technology. The width of a single beam is 190 mm, and the width of the beam at the joint is 110 mm. Three shots were fired with a Glock 17 pistol chambered for 9×19 (marked red in Figures 1 (b), (c). Then one with the firearm APC556 (marked green in Figure 1 (b), (c).

(a) (b) (c)

Figure 1. (a) Dry pine log samples after shooting - side view; dimensions in red. Log width 190 mm, narrowest joint 110 mm; (b) (c) Samples of pine log after firing (b) bullet entry side (c) bullet output side; the red mark indicates the location of the three bullets fired by the Glock 17, and the green mark indicates the bullets fired by the larger APC556.

Plywood tests

Plywood samples of 28 mm (1 plate), 56 mm (2 leaves), and 84 mm (3 plates) with dimensions $40 \times 60\,\text{cm}$ were tested. Only the Glock 17 was fired, one shot at each target. Figure 2 shows the side view and the bullet hole as it enters and the damage to the material as it exists. The damage to the target is due to the shape and speed of the bullet. As the bullet starts to penetrate the material, its speed decreases.

(a) (b) (c)

Figure 2. 84 cm plywood target - 3 plates assembled; (a) side view; tripod shown; (b) bullet input; (c) bullet output side.

Only for the 3-ply (Figure 2), the Glock 17 bullet embeds between the second and third ply. The surface resistance explains it. So, the penetration depth P is about 56 mm. The thinnest specimens (28 mm and 56 mm) were also excluded from the result analysis as the bullets passed through them. However, the APC556's bullets penetrated all targets of plywood.

CLT tests

(a) (b) (c)

Figure 3. 130 cm (30-20-30-20-30 mm) thick CLT target; (a) side view; tripod shown; (b) bullet input; (c) bullet output.

The third CLT specimens tested were four spruce CLT specimens of different thicknesses: 60 mm (20-20-20 mm), 80 mm (30-20-30 mm), 100 mm (20-20-20-20-20 mm), 130 mm (30-20-30-20-30 mm) cut in sizes $50 \times 50\,\text{cm}$. The greater thickness materials are not considered, as it would not be financially efficient to use the given materials. The 60 mm, 80 mm, and 100 mm samples were shot with a Glock 17 pistol, and usage of other weapons was not continued, as automatic bullets are expected to pass through them.

CLT material with 60 mm, 80 mm, and 100 mm thickness penetrated both bullet sizes. However, the 130 mm sample (see Figure 3) was fired with both a handgun and a semi-automatic rifle, and it must be said that it did not withstand both firearms. So, the penetration depth exceeds the thickness of the target.

Theoretical penetration depth

Theoretical values of the penetration depth P are obtained from formula (2) and shown in Table 2 with the values given. The wood samples, their thicknesses used in the experiment, the weapon, the Glock 17 handgun, and APC556 firearms used to shoot them are named (see Table 1 above).

The parameters α and β are taken from 7, where Pine log coefficients are equated to European pine (α = 0.028 kg/m and β = 1500 kg·m/s^2). Spruce CLT was taken from Douglas spruce parameters (α = 0.013 kg/m and β = 2300 kg·m/s^2). However, birch plywood was averaged among other deciduous trees (low-value α = 1·10-13 kg/m and high-value β = 9000 kg·m/s^2); therefore, the density of Merbau wood is closer to a birch's density.

The weapon (the Glock 17 handgun, APC556 firearms) used, the mass of the projectiles is 8 grams, and 9 grams, velocity of the projectiles is 400 m/s and 800 m/s, , so the calculated penetration depth is shown in the P column, compared to specimen width h.

The theoretical calculations (Table 2), which were carried out after the experimental ones, proved the penetration depth results of the practical tests (shooting).

Table 2. Theoretical calculations of bullet penetration depth P

	Specimens	Width h, m	Theoretical penetration depth P, m	
			Glock 17 m = 8 g v = 400 m/s	**APC556** m = 9 g v = 800 m/s
A	Pine log	0.110	0.198	0.412
		0.190		
B	Birch plywood	0.028	0.071	0.224
		0.056		
		0.084		
C	Spruce CLT	0.060	0.198	0.530
		0.080		
		0.100		
		0.130		

Pine logs were 110 mm and 190 mm, but calculations using the Poncelet model proved that it must be more than 198 mm by width for a Glock 19 and more than 412 mm by width for an APC556 to protect the temporary building. Birch plywood was 28 mm, 56 mm, and 84 mm thick, while calculations proved that it must be more than 71 mm by width for a Glock 19 and more than 224 mm by width for an APC556 to protect the temporary building. Spruce CLT was 60 mm, 80 mm, 100 mm, and 130 mm thick, while calculations proved that it must be more than 198 mm by width for a Glock 19 and more than 530 mm by width for an APC556 to protect the temporary building (Figure 4). Only three panel-thick plywood does not exceed the depth of penetration. The theoretical depth of embedment is calculated to be 0.071 m (71 mm), whereas the triple thickness of the plates is 84 mm. The theoretical results explain the experiment result in those bullets passing through the other samples, but not the 0.084 m plate. All the projectiles fired by the APC556 passed through all the specimens, thus confirming the experiment results.

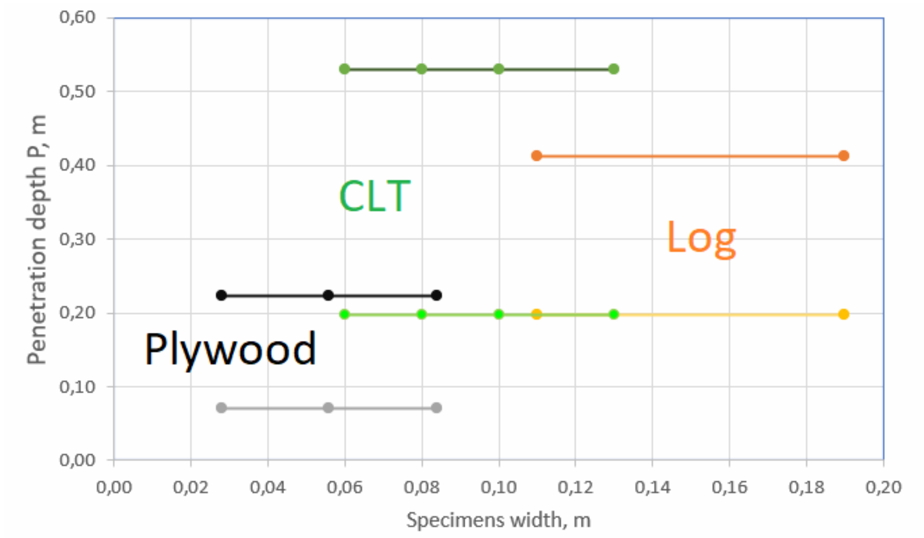
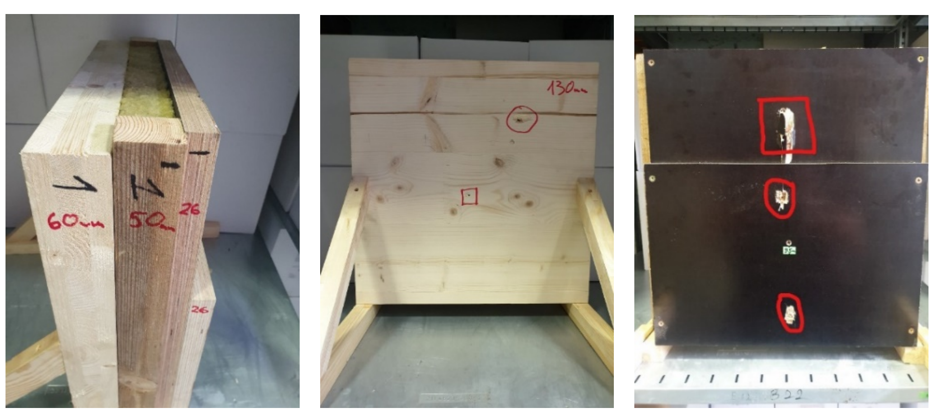


Figure 4. Penetration depth P for each group of specimens.

Combined material

Observations from the first shooting implied the necessity of the upgraded material, thus resulting in a combined panel (Figure 5) consisting of CLT 60 mm (20-20-20 mm), insulation from semi-rigid rock wool 50 mm by Paroc, and plywood 26 mm or 52 mm (26-26 mm). The thermal conductivity of the combined panel was calculated theoretically at $U = 0.474$ W/(m^2·K).



(a) (b) (c)

Figure 5. Combined panel (a) side view; (b) bullet entrance; (c) bullet output.

The first bullet fired by the Glock 17 from a 5 m distance passed through CLT (60 mm), rock wool, and one layer of plywood (26 mm). A second Glock 17 bullet fired from a 5 m distance penetrated the CLT (60 mm) and two layers of plywood (26 mm + 26 mm) and stopped in the middle of the plywood plates.

After examining the samples and measuring the penetration depths, they were 82 mm and 85 mm (Figure 5). Theoretical calculations using an inverted formula of (2) showed the coefficients: inertial stress contribution $\alpha = 0.005 - 0.015$ kg/m and parameter $\beta = 4000 - 6000$ kg·m/s^2, getting the penetration depth $P = 0.100 - 0.125$ m.

4. Discussion

Projectiles from both weapons passed through the pine log target. Theoretically, wood with a higher moisture level than 18% would have improved resistance; however, in the construction, including temporary buildings, wood materials are used up to 18% of moisture. Log cabins have been historically widely used, thus leading to the impression of stable construction that could protect against ballistic attacks. However, it must be concluded that a standard size log house does not protect against bullets.

To ensure the ballistic protection of the temporary buildings, CLT panels must be more than 198 mm by width for a Glock 19 and more than 530 mm by width for an APC556. However, 130 mm is the optimal size for construction and economic considerations; this can be estimated as material not financially efficient.

The APC556's bullets penetrated all targets of plywood placed together. From a theoretical perspective, it would be possible that higher bullet resistance would be seen if three plates of the plywood material were separated from each to have air between the plates. The bullet would have a more challenging time penetrating the surface of the next element, suppressing its energy, thus not allowing it to pass through the whole specimen.

Thus, the panel of 84 mm plywood and a particular combined panel are suggested for the unclassified buildings. None of the other materials – logs up to 190 mm, CLT up to 120 mm, and plywood less than 84mm used in the first part of the experiments are suggested.

Wood and its products separately are not suitable materials for dealing with external threats such as bullets. Other non-standard solutions should be sought, such as replacing the top layer with aramid or a high-density polyethylene board, spacing timber apart (as air has a high resistance), or experimenting with layered structures, including an insulation layer and/or composite material. Improved wood structure bullet-proof buildings could be used for short-stay accommodation in non-standard situations, where the building would be relatively quick and easy to assemble and repair.

Theoretical calculations of the penetration depth showed reliable results, which confirmed the experimental data. Therefore, selecting the test sample/wall thicknesses should be based on theoretical calculations, reducing the number of samples and tests. Hence the combined material was generated for the next shooting round, where the layers have different densities, and it helped improve the ballistic response.

5. Conclusions

The experimental results demonstrate that a panel of 84 mm plywood and a combined panel are suggested for the unclassified buildings. None of the classic wooden materials – logs up to 190 mm, CLT up to 120 mm, and plywood less than 84 mm used in experiments are suggested for ballistic protection.

Theoretical calculations of the penetration depth showed reliable results, which confirmed the experimental data. Therefore, the test sample/wall thickness selection was confirmed based on theoretical calculations. Hence, the combined material was generated for the second shooting consisting of CLT 60 mm (20-20-20 mm), semi-rigid insulation of rock wool 50 mm by Paroc, and plywood 26 mm or 52 mm (26-26 mm) was generated. A double layer of plywood stopped the projectile.

The experiments confirm that wood and wood-based products are not suitable materials for dealing with external threats such as all but the weakest bullets. Other non-standard solutions should be sought, such as panels with insulations or other improved wood panel alternatives such as replacing the top layer with aramid, polyethylene board, spacing timber apart (as air has a high resistance) or experimenting with layered structures including an insulating layer and/or composite material.

Such bullet-proof buildings could be used for short-stay accommodation in non-standard situations for stray bullets, where the building would be relatively quick and easy to assemble.

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