CLT Wall for Bullet-Safe Temporary Buildings

Elina Barone*, Ingars Grinevics, Baiba Gaujena, Martins Vilnitis

Institute of Civil Engineering, Faculty of Civil and Mechanical Engineering, Riga Technical University, Kipsalas street 6a, Riga, LV-1048, Latvia

*Corresponding author: **elina.barone@rtu.lv**

https://doi.org/10.5755/j01.sace.37.1.38395

JSACE 1/37

CLT Wall for Bullet-Safe Temporary Buildings

Received 2024/08/06

Accepted after revision 2025/02/26

Abstract

The authors propose a handgun bulletproof load-bearing 140 mm cross-laminated timber (CLT) wall with knitted aramid (Kevlar) fabric in two layers for tangling the bullet and a reference wall without a Kevlar layer. The study compares the layers in which the added aramid sheet should be placed for northern areas to allow people to have acceptable insulated conditions in temporary houses while being protected from potential bullet external threats. Results showed that a 140 mm CLT layer with 200 mm mineral wool insulation with a Kevlar layer between the insulation layer and CLT is enough to stop the bullet if fired up to 341.6 m/s with a firearm. Perforation data for CLT material samples with various thicknesses have been collected and analyzed. A metal rod and a ruler determined the penetration depth for ogive-nose projectiles when they did not fully perforate the panel. The results show the ballistic properties of CLT material. The results will be proposed to the construction industry of wooden buildings as a bonus for those whose security is significant.

KEYWORDS: building; bulletproof; CLT wall; handgun; Kevlar.

Introduction

In a riot, people often are forced to stay out of comfort habitat conditions. Temporary accommodation, usually unclassified buildings (Borodinecs et al., 2022), can be offered as short-term shelter buildings, where people should be optimally provided with adequate and safe living conditions. Preferably, the buildings are ballistically protected. CLT walls are increasingly used as load-bearing frames in building structures, including unclassified mobile buildings suitable for human occupancy. CLT can be compared to a larger scale of plywood (Brandner et al., 2016; Sanborn, 2018); it is pre-prepared, glued, has an anisotropic structure, and the mechanical properties - strength, durability, and ballistic resistance - may vary depending on the age, species and growing conditions of the tree, including knots. (Boatright & Garrett, 1979; Koene et al., 2013; Koene & Broekhuis, 2017; Melderis, 2008b, 2008a; Nardin A. et al., 2000; Zhang et al., 2024). This difference can also be found within the same sample (Sanborn, 2018). Wood composites' cross-laminated structure reduces the material's anisotropy and mechanical properties, making laminated materials more predictable and reliable than solid wood. (Hughes, 2015; Koene & Willemsen, 2023)

The bullet's action on the target starts with a short high-pressure phase, followed by the spread of shock waves at constant energy pressure, simultaneously forming a bullet crater, ending with a recovery phase (shrinkage of the bullet crater and expansion of the material around the crater under negative pressure). (Christman & Gehring, 1966; Sanborn, 2018) The projectile's penetration into the timber increases with the impact velocity, and for softer timber, these parameters are close to linear dependence. The projectile's penetration depth depends mainly on the ability of the target material to reduce the kinetic energy, which is determined by the hardness of the wood and the direction of the wood fibers. (Koene et al., 2013; Koene & Broekhuis, 2019).

The penetration capacity of a bullet depends on two sides - the characteristics of the bullet and the characteristics of the material. The impact of each characteristic on ballistics is shown in Table 1.

Journal of Sustainable Architecture and Civil Engineering
Vol. 1 / No. 37 / 2025
pp. 97-108
DOI 10.5755/j01.sace.37.1.38395

Table 1

Effect of material properties on ballistic resistance (Dresch et al., 2021)

Characteristics	Ballistic impact
density	weight of the system
hardness	damage of the projectile
Young modulus	stress wave propagation
fracture toughness	multi-hit resistance
fracture mode	energy absorption

Ballistic testing of CLT indicates that the material's inherent penetration resistance is significantly greater than that of dimension lumber and plywood used in current common temporary military structures. (Sanborn, 2018; Sanborn et al., 2019). Currently, wood is underrated, and CLT has not been mass-produced for use as a blast shield due to the low strength of wood compared to steel and concrete. (Sanborn, 2018). However, wood is up to five times less dense than concrete and less than 10 times as dense as steel. Timber is simpler to transport, assemble, and repair, and wood is more affordable than bulletproof opaque glass. Hence, the properties of CLT composites, combined with the energy-absorbing capacity of wood panels, make it a promising direction for use in temporary military structures (Sanborn, 2018). However, there is a lack of research on bullet-proof wall-building materials. High-ball speed studies (Lo Ricco et al., 2023) conclude that steel-reinforced softwood layups are the most viable solution to develop and include in engineering models. In this study, CLT is combined with a layer of Kevlar fabric. Kevlar has a unique combination of high strength, modulus, toughness, and thermal stability. Kevlar has an application where weight reduction, increase in strength, and corrosion resistance significantly improve safety and efficiency. A thin blanket can be structural reinforcement or ballistic protection, tangling the bullet. It is lightweight and easy to integrate (Reashad et al., 2013). Kevlar fiber is often used in ballistic experiments, especially in body armour tests (Anand et al., 2018; Haro Albuja et al., 2016; Majumdar et al., 2013; Salman et al., 2016).

The projectile's penetration depth P depends on the bullet's deceleration in the target and the projectile's velocity, as shown in Poncelet **Eq. (1)**.

$$P = \frac{m_p}{2\alpha} \cdot \ln\left(1 + \frac{\alpha v_i^2}{\beta}\right) \tag{1}$$

Where: P – final penetration depth, mm; m_p - the mass of the projectile, kg; α – represents the contribution of inertial stresses, kg/m; v_i – impact 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. The parameters α and β usually are determined experimentally from the penetration data. (Koene & Broekhuis, 2017)

This, if $\alpha = 0$, is what the Robins-Euler model for penetration depth is about:

$$P = \frac{m_p v_i^2}{2\beta} \tag{2}$$

The Poncelet model works better than the Robins-Euler model in describing projectile penetration. (Koene & Willemsen, 2023) To calculate the depth of penetration of armour made of several layers (plies) of materials, it is necessary to determine the layer where the projectile will stop at v=0. The calculation must be performed separately for each target layer (ply), determining which layer the projectile will be trapped (stop in its motion). However, experimental results in various graphs are used rather than calculations for practical purposes. (Melderis, 2008a) Accurate measurement of deceleration during penetration is difficult to capture with most materials. Instead, the penetrator depth measurements from experiments for various velocities can be used to determine material-dependent constants in the empirical relationship. (Sanborn, 2018)

Materials and Methods

Three walls were tested. Two walls (A, B) with a layer of aramid fabric (Kevlar) on each side for the CLT specimen and without a layer of aramid as a reference wall (specimen C). The wall consisted of a 12.5 mm plasterboard, a 200 mm mineral wool layer, a 140 mm CLT layer (40-20-20-20-40 mm), and a 12.5 mm fire-resistant plasterboard as required by fire safety requirements. The wall construction was based on the wall composition provided by SIA CLT Profi (Latvia), which has an 80 mm thick CLT block as standard, but for ballistic purposes, this is replaced by a 140 mm thick block. The adhesive is usually urea formaldehyde used in the CLT materials. The wall panel is normally supplemented with a vapor barrier film and a finishing material that has negligible ballistic resistance and was, therefore, not used in the experiment. There are also wood battens on which the finishing material is supported, which would have significant ballistic resistance. However, they do not cover the whole panel. In the experiment, aramid woven Kevlar was added in two layers in two variations - between the thermal insulation and the CLT (sample A) and between the CLT and the fire-resistant gypsum board (sample B). Shooting was carried out on both sides of the CLT wall, checking how and whether the CLT layer stopped the bullet. The thermal conductivity of the tested wall was calculated theoretically at U=0.154 W/(m^2·K). According to theoretical calculations, the thickness of the mineral wool could have been lower, i.e. 150 mm, to meet the requirements of LBN 002-19 regarding the maximum values of thermal conductivity of walls of residential buildings.

The wall composition for wall B (Kevlar fabric between CLT and fire-resistant gypsum board), layer thicknesses, existing density (measured and weighed specimens), and relative theoretical density are shown in Table 2 and Figure 1. According to the manufacturer's data, the CLT material is defined as the C24 class for solid wood. As can be observed, the densities are nearly the same as the theoretical densities, except for CLT.

Table 2

CLT wall composition for sample B, thermal conductivity U=0.154 W/(m^2·K)

No.	Wall composition	Thickness, mm	Experimental density, kg/m^3	Theoretical density, kg/m^3
1	Gypsum plasterboard grey Knauf mini GKB	12.5	641.6	641.0
2	Mineralwool Knauf Insulation Ekoboard	200	13.9	13.8
3	CLT, *CLT Profi*	140	461.7	420 (wood C24)
4	Kevlar fabric x2	2x0.9	217.8	222.2
5	Gypsum plasterboard Knauf red GKF	12.5	829.8	800

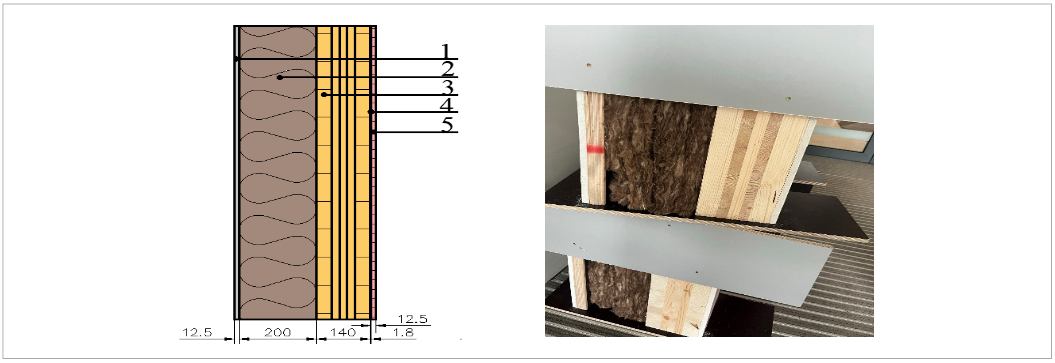


Fig 1

CLT wall (sample B) - schematic representation of the layers (see Table 1) and a specimen, side view. (The red mark is the wooden frame used to fix the plasterboard. It is not included in the wall and does not affect the experiment as it is not in the bullet's path.)

Conventional gypsum plaster has low ballistic resistance (Barone, Vetra, et al., 2023). It is used in CLT walls as a fire protection layer, which European regulations require for fire safety in residential timber buildings. The Kevlar fabric used is knitted (2-strand knit) rather than woven. The selection was based on market availability. Knitted Kevlar fabric is used as additional protection in abrasive environments, such as in the clothing of people in sports such as motorsports.

The samples (Fig. 2a) were stored for 2 months in laboratory conditions at 19 °C and 12 % humidity. The moisture content before testing was 5,3 % for CLT material and 6,5 % for gypsum boards.

This study was limited to one handgun and one type of ammunition. The weapon used (Figure 2a) in the experiment is a CZ 75 semi-automatic handgun manufactured by ČZUB in the Czech Republic. It weighs 0.77 kg. Caliber 9x19 mm Parabellum. Its projectile makes a noise of 157-162 dB when fired. Therefore, a headset is an obligatory part of the safety kit, and additional earplugs as necessary. The firing angle (the projectile axis angle relative to the obstacle's surface) was 90 degrees. However, this could vary considerably since the shooter was a human professional rather than a device. The possibility of ricochet was excluded.

The AK-47 automatic weapon was fired once in a test mode (see Figure 4b). The decision was made not to proceed with further experiments with this weapon, as experience (Barone et al., 2022) shows that it passes through all wood or wood composite samples and bullets with velocities greater than 440 m/s (corresponding to class BR1-BR4, standard EN 1063, or FB1-F4, DIN EN1063) are not intended to be considered in this study.

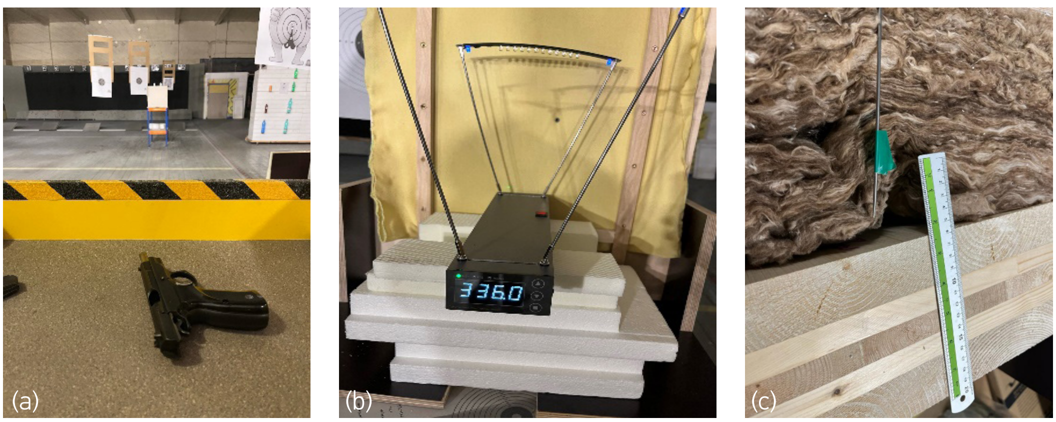


Fig. 2

CLT composite wall experiment. CZ 75 weapon was used (a), and a velocity measuring velocimeter and a knitted Kevlar was used (b), as well as depth measurement (c)

The temperature in the experimental room or shooting range was +10.4 °C and the humidity 72 %, which had minor effects on the experiment, as the samples were in the shooting range for one hour. Two N\P Slingshot Speed tester chronographs (see Figure 2b) with ≤1% measurement tolerance and 1 m/s accuracy were used to measure the velocities of the bullets. The choice of the velocimeters coincides with market availability. The velocimeter was placed before and after the target material, as close to the wall sample as possible. The penetration depth was measured with a steel rod and a ruler (Figure 2c), and the accuracy is ±1 mm (smallest section value) to the back of the penetrated projectiles. The configuration of the ballistic experiment is shown in Figure 3. The bullet firing distance is from the weapon's barrel to the specimen due to bullet entrapment or to the ballistic block in the case of bullet penetration.

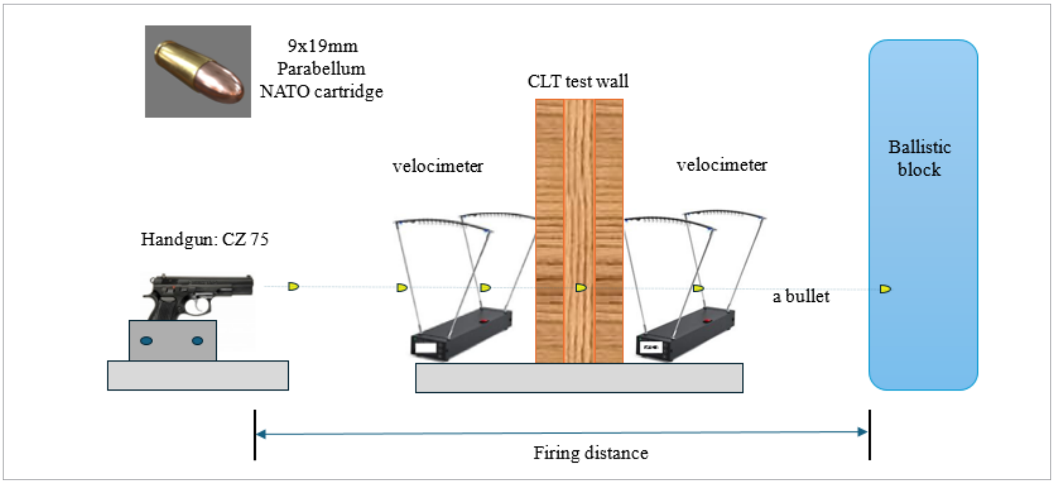


Fig. 3

Configuration of the ballistic workbench

Experimental Part

Although according to NIJ standard-0108.01, Ballistic Resistant Protective Materials, and EN 1063 Standards for ballistic resistant protective materials, the firing distance is 5 m for firearms up to 440 m/s, this experiment was fired from 8.315 m and 9 m (two rounds) for the convenience of the shooter and sample placement. The standard specifies a sample size of 500 x 500 mm. The test qualifies as Class BR2 according to EN 1063 or Class 1 according to UL752 as defined by the Parabellum cartridges used. 3-5 shots were fired at each wall. Although the number of specimens is sufficient, a larger data set could be useful for future work.

Unlike other ballistic studies (Koene & Broekhuis, 2017; Lo Ricco et al., 2023; Sanborn et al., 2018), the experiment used a constant bullet entry velocity. The average velocity of the bullet fired from the CZ 75 weapon before the bullet entered the sample was 341.8 m/s (samples A and B), measured from 5 measurements. In the second experimental pass (sample C), the average velocity of the bullet before the bullet's entry into the sample was 339.7 m/s. This is under NIJ standard-0108.01, where the initial velocity of a 9 mm bullet should be 332 ± 12 m/s.

When the bullets were fired from the outside of specimen A (starting with the grey plasterboard, Figure 4a), they remained in the CLT material to an average depth of 91.3 mm. The Kevlar fabric did not completely stop the bullets as intended; they penetrated through the fabric and embedded in the CLT. The average penetration depth throughout the wall was 303.8 mm (12.5 + 200 + 91.3 mm).

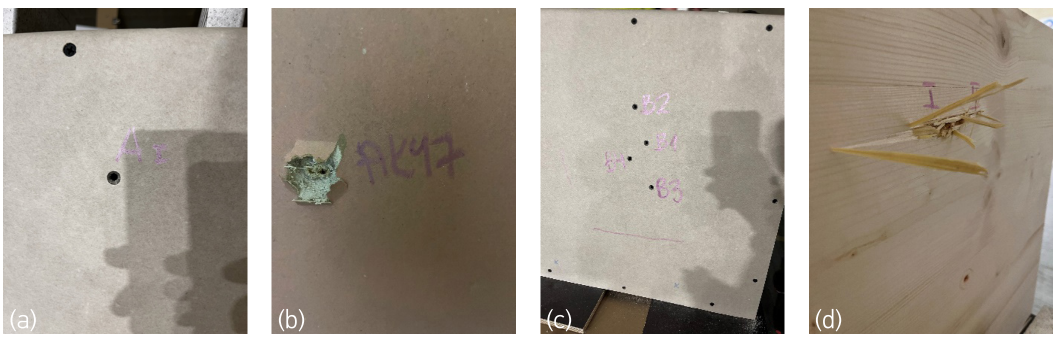


Fig. 4

CLT wall experimental samples after shooting (a-d)

For the wall of sample B, two of the 4 bullets were absorbed by the wall (Figure 4b), and the other two could not be stopped. The average residual velocity of the 2 bullets was 56.8 m/s. Therefore, after reduction, the wall could reduce the bullet velocity by 285.0 m/s, calculated from the average bullet velocity before entering the sample of 341.8 m/s. The average penetration depth of bullets in the wall is 342.8 mm (12.5+200+1.8+128.5 mm). The bullets penetrated the CLT material to an average depth of 128.5 mm without reaching the Kevlar fabric layer.

Comparing specimens A and B, it can be concluded that the Kevlar fabric creates additional resistance as specimen A's penetration depth is less than specimen B's, and specimen A stopped all 4 bullets. This is probably because the bullet must cross an additional surface to continue the motion. Even if the bullet is only fired through 2x0.9 mm Kevlar fabric, it only reduces the velocity by 5 m/s on average (see Figure 2b).

The reference wall C without Kevlar was penetrated in both directions by the bullet; its velocity after leaving the wall was, on average, 43.5 m/s, and the wall reduces the velocity by 296.5 m/s, which is similar to when the Kevlar fabric is in the wall, so it can be concluded that the knitted Kevlar fabric does not have a very large effect on the ballistic resistance due to its structure. The next study should be a ballistic experiment with woven (rather than knitted) Kevlar fabric, which, according to fiber theory, is better at capturing and dissipating the kinetic energy of a bullet along the length of the fiber.

The results of the shooting are tabulated in Table 3.

Table 3

Three CLT wall shooting results

Sample	No	Velocity of projectile			Penetration depth*	
		v_0, m/s	v_r, m/s	Δ_v, m/s	in whole wall, mm	in CLT, mm
Kevlar between insulation and CLT	A	341,8	0	0	303,8	91,3
Kevlar between CLT and fireproof gypsum	B	341,8	56,8	285,0	342,8	128,5
Reference wall without Kevlar	C	339,7	43,5	296,5	0	0

* Excluding the dimensions of the deformed sphere, as the specimens were not "opened" but measured with a metal rod to the back of the bullet.

Shooting from the other side of the wall, with the fire-resistant plasterboard in front, gives different results; for a non-symmetrical layered wall, which side of the material is fired from is important. Sample A fired from the other direction. The fire-resistant gypsum board with additional glass fibers in a structure and the 140 mm CLT wall stopped the bullet as it penetrated 52.5 mm deep, or only 40 mm inside the CLT material. This means the Knauf Red fire-resistant plasterboard with fire reaction class A2-s1, d0 has a relatively high ballistic resistance.

For the second study, 80 mm, 100 mm, and 140 mm thick CLT wall specimens were tested by shooting through them 3-5 times and measuring the bullet velocities before and after the bullet passed through the material. The difference in velocities shows how many meters per second (energy) the material takes from the bullet away.

The CLT 140 mm (40-20-20-20-40) sample had an average entry speed of 342.9 m/s and an average residual speed of 150.3 m/s. This resulted in an average deceleration of 192.6 m/s for the CLT 140 mm sample. The CLT 100 mm (20-20-20-20-20) sample had an average entry speed of 339.7 m/s and an average residual speed of 178.7 m/s. This resulted in an average deceleration of 192.6

m/s for the CLT 100 mm sample. The CLT 80 mm (30-20-30) sample had an average entry speed of 339.7 m/s and an average residual speed of 218.6 m/s. This resulted in an average deceleration of 121.1 m/s for the CLT 80 mm sample.

Results

The acquired results are presented in Table 4. One version of the results is to calculate the ability of 1 mm of material to reduce the resistance of a bullet, expressed in meters per second. Considering the wood is anisotropic, and CLT is a layered material, including the adhesive layer between the CLT boards, this value is approximate, being an average between many measurements. However, the results show that the ability of 1 mm of CLT material to stop a bullet is, on average, 1.61 m/s per 1 mm. When comparing CLT 140 and 100 mm, there is no difference in the number of layers, but there is a difference in the thickness of the outer layers. The thickness of the layers is not the decisive criterion.

Table 4

CLT panel firing results

Thickness of the CLT sample	Layers	Initial velocity v_0, m/s	Residual velocity v_r, m/s	Absorbed velocity Δv, m/s	Δv on 1 mm, m/s · mm	Penetration depth, mm
80	30-20-30	339.70	210.85	128.85	1.61	Penetrated
100	20-20-20-20-20	339.70	178.67	161.03	1.61	Penetrated
140	40-20-20-20-40	341.83	117.77	225.90	1.61	Penetrated
150	30-30-30-30-30-30	Stopped			-	105.0
240	40-40-20-40-20-40-40	Stopped			-	122.5
260	40-40-30-40-30-40-40	Stopped			-	145.5

In **Figure 5**, the horizontal line is the velocity of the CZ 75 revolver before entering the material (v_o=341.83 m/s). The blue sloping line is the guaranteed absorbed velocity of each CLT block thickness, expressed in meters per second. The intersection of the bars with this line ensures that the CLT material is guaranteed to stop the bullet. Theoretical calculation of the depth of penetration of the bullet in the CLT material using Poncelet's formula (**formula 1**) gave 156 m. (Barone et al., 2022)

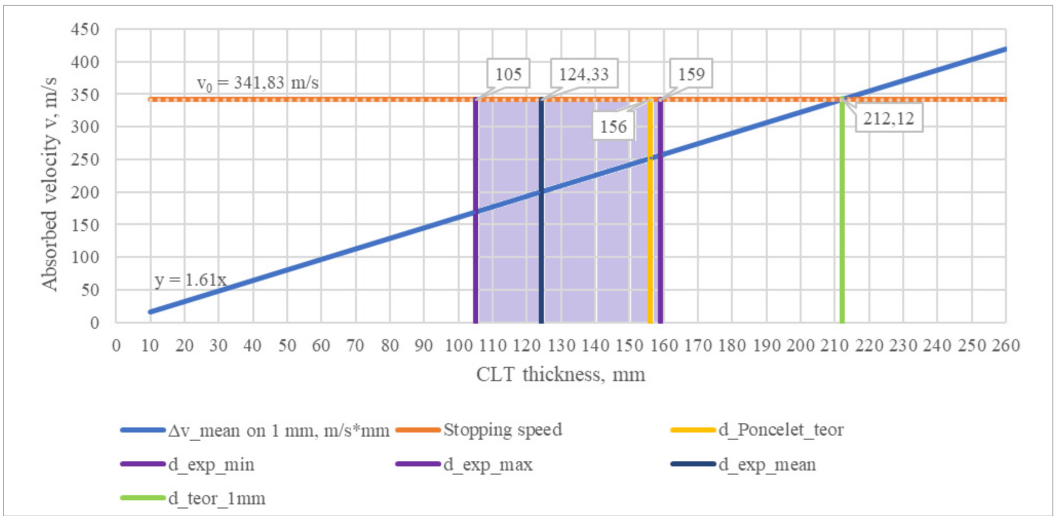


Fig. 5

CLT material potential absorbed velocity. The purple area shows the penetration depth of the experimental data in CLT material

In the graph (Figure 5), the intersection shows the limit of the thickness of the CLT material that will absorb the bullet. This is, on average, 212.12 mm (green vertical line), which is the size that is guaranteed to stop a bullet. The theoretical straight line at panel thickness d=156 mm (yellow), calculated with Poncelet's formula, is also plotted vertically. The purple area shows the penetration depth of the experimental data in CLT material. Minimum (105 mm) and maximum (159 mm) penetration depth in all experiments. The average experimental penetration depth is 124.33 mm. As can be seen, the tabular result of 212.12 mm is much higher than the theoretical and experimental evidence. Therefore, 212.12 mm could be the guaranteed CLT thickness stopping BR2 class weapons.

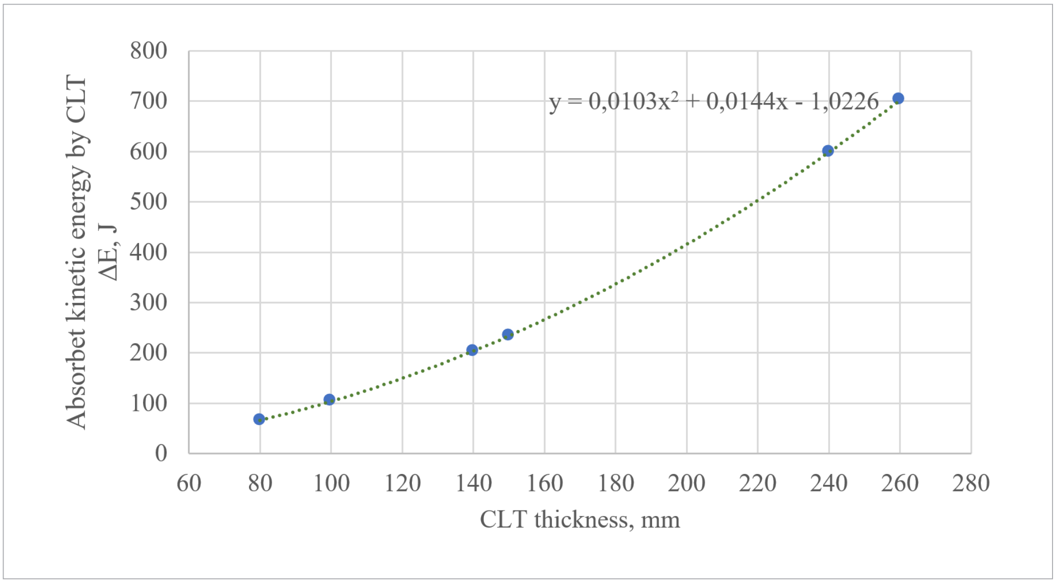
The graph (Figure 5) predicts the thickness of the CLT panel needed to stop a bullet or part of a bullet at a given speed. For example, to stop a CZ 75 bullet at an average speed of 340 m/s, a 212.12 mm CLT wall would be selected. However, since it is sufficiently heavy and thick, another option would be, for example, a 90 mm CLT block that would stop 150 m/s or 44% of the required speed and an additional layer of UHMWPE material (Barone, Velicko, et al., 2023) or an aramid panel (Borodinecs et al., 2022), but similar studies are needed to calculate these required thicknesses.

In the experiment on a 240 mm (7-layer wall, 40-40-20-40-20-40-40) CLT wall specimen, the average depth of penetration of a bullet was 122.5 mm, while for a 260 mm (7-layer wall, 40-40-30-40-30-40-40) specimen the average was 145.5 mm, while for a 150 mm (30-30-30-30-30-30) wall, 2 bullets passed through, and three bullets formed a penetration depth of 105 mm on average. These results are consistent with the conclusion that the guaranteed thickness of the CLT prevents bullet penetration.

The CLT blocks absorb a certain amount of the bullet's kinetic energy. The amount of kinetic energy depending on the CLT blocks thickness of the CLT blocks is shown in Figure 6, if the mass of the bullet is 0,008 kg. The curve is parabolic. In this way, the absorbed energy of each thickness of CLT material can be predicted kinetic energy.

Fig. 6

CLT material potential absorbed kinetic energy



Further, according to formulae 1-2, the coefficients α and β for CLT material, which are not found in the scientific literature, were calculated using the Poncelet and Robins-Euler equations. Only (Koene & Broekhuis, 2017) determined that the material parameters for pine wood (softwood, from which CLT is also made) have an inertial stress coefficient α = 0.028 kg/m and a material strength parameter β = 1500 m/s^2.

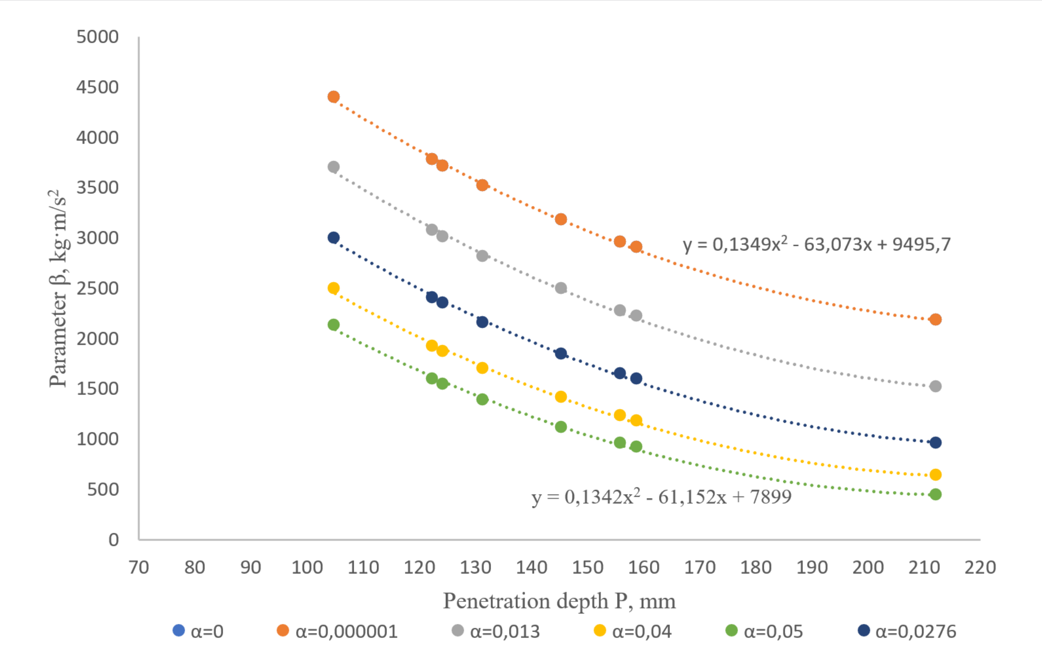


Fig. 7

Material strength parameter β for CLT material depending on the experimentally obtained penetration depth P and the inertial stress coefficient α

Based on the experimental penetration depth P values, the material strength parameter β values are 916-4396 kg·m/s² for CLT material. Based on the guaranteed penetration depth P values, the material strength parameter β values are 438-2125 kg·m/s² for CLT material. The graph (**Fig. 7**) shows that the parameter β is a second-order polynomial or parabola. Checking the Poncelet formula (1) and comparing with the Robin-Euler formula (2), the values of β are almost identical (the upper curve is double), that is, when the internal stress coefficient α of the material is close to zero or when α is already taken as zero by the Robin-Euler formula (2).

At the average penetration depth obtained, P=124.33 mm, the average value of the strength parameter of the CLT material is β=2345 kg·m/s² if the internal stress coefficient of the CLT is α=0.0276 kg/m. Compared to pine wood (Koene & Broekhuis, 2017), if α=0.028 kg/m, the CLT of spruce wood is β=2328 kg·m/s².

In the equation for penetration (**formula 1**), the values of α and β depend on each other. P is assumed constant, so if β varies, so does α.

In the graph (**Fig. 8**) showing the dependence of the internal stresses α on the parameter β, which describes the internal stresses in the CLT material, it can be observed that the values of α range from 0 kg/m (minimum value) to 0.071 kg/m for a given penetration depth P. The larger the penetration depth P, the smaller the values of α (and β). The shaded area shows the possible region of α for CLT material. So, the smallest penetration depth P=105 mm gives the largest α values. The curves of the graph have a second-order polynomial character. The brown shaded area is the limit of the coefficient α. The light brown shaded area represents the values of the guaranteed penetration depth, which cannot be achieved.

Ballistic studies have additional issues of blast safety and shrapnel hazard. This study is limited by not examining the response of the materials to an explosion; it was not assumed in these experiments. However, a thick cloth protected the shooting range from the bullet fragments and prevented the departing bullets' residues from affecting the shooting range floor and walls. In this experiment, the allowable handgun velocities range up to 440 m/s. One interpretation of the additional relevance of these limits is that grenade attacks produce fragments and debris that fly at the velocity obtained in the explosion, which decreases rapidly.

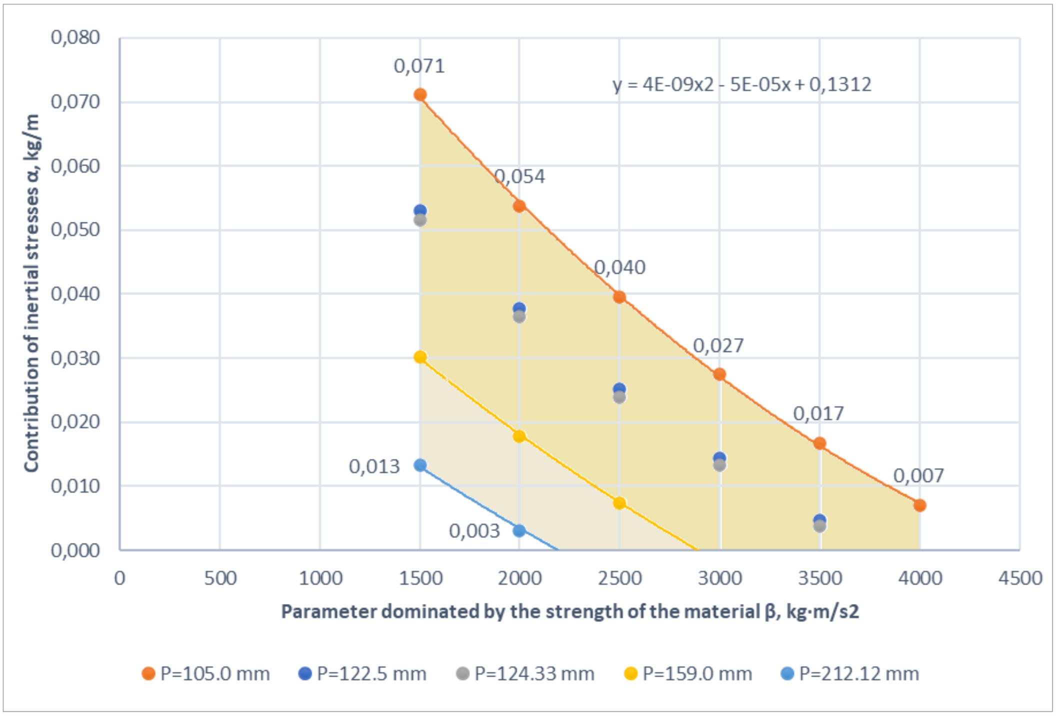


Fig. 8

Material internal stress coefficient α depends on the value of the material strength parameter β for CLT material at the experimentally obtained penetration depth P

Conclusions

- From the experiment results, it can be concluded that the knitted Kevlar fabric affects the ballistic resistance, but it is not significant due to its structure.
- Results showed that a 140 mm CLT layer with 200 mm mineral wool insulation with a Kevlar layer between the insulation layer and CLT is enough to stop the bullet if fired up to 341.6 m/s.
- Experimental data showed that CLT material with a thickness of 212.12 mm is the guaranteed thickness to stop BR2 class weapons by EN 1063.
- Every 1 mm of CLT material can stop 1.61 m/s, experimentally proved. The chart shows the ability of each CLT thickness to stop the bullet at a certain velocity/kinetic energy.
- At an average penetration depth P=124.33 mm of CLT, the average value of the CLT material strength parameter is β=2345 kg·m/s2 if the CLT internal stress coefficient α=0,0276 kg/m. These values help determine the CLT material's average penetration depth at different bullet velocities and masses.

Acknowledgment

This work has been supported by the European Social Fund within Project No 8.2.2.0 /20/I/008, "Strengthening of Ph.D. students and academic personnel of Riga Technical University and BA School of Business and Finance in the strategic fields of specialization" of the Specific Objective 8.2.2 "To Strengthen Academic Staff of Higher Education Institutions in Strategic Specialization Areas" of the Operational Program "Growth and Employment".

References

Anand, V., Edwin, A., Justus, D., Prasanna, K., Ramesh, S., & Arun, S. (2018). Energy absorption and ballistic impact behavior of Kevlar woven fabrics. www.tjprc.org

Barone, E., Gaujena, B., & Videmanis, J. (2022). Projectile penetration depth into wood-based frames of unclassified buildings. Far East Journal of Mathematical Sciences (FJMS), 11-20. https://doi.org/10.17654/2229451122002

Barone, E., Velicko, E., Gaujena, B., & Vilnitis, M. (2023). Plywood Panel with UHMW Polyethylene Board Ballistic Resistance. Journal of Sustainable Architecture and Civil Engineering, 32(1), 233-243. https://doi.org/10.5755/j01.sace.32.1.32822

Barone, E., Vetra, R., Gaujena, B., & Vilnitis, M. (2023). Ordinary gypsum plasterboard and Knauf Torro gypsum plasterboard bullet-proofing. Journal of Physics: Conference Series, 2423(1). https://doi.org/10.1088/1742-6596/2423/1/012016

Boatright, S., & Garrett, G. (1979). The effect of knots on the fracture strength of wood - I. A review of methods of assessment. https://doi.org/10.1515/hfsg.1979.33.3.68

Borodinecs, A., Geikins, A., Barone, E., Jacnevs, V., & Prozuments, A. (2022). Solution of Bullet Proof Wooden Frame Construction Panel with a Built-In Air Duct. Buildings, 12(1). https://doi.org/10.3390/buildings12010030

Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., & Thiel, A. (2016). Cross laminated timber (CLT): overview and development. European Journal of Wood and Wood Products, 74(3), 331-351. https://doi.org/10.1007/s00107-015-0999-5

Christman, D. R., & Gehring, J. W. (1966). Analysis of High-Velocity Projectile Penetration Mechanics. Journal of Applied Physics, 37(4), 1579-1587. https://doi.org/10.1063/1.1708570

Dresch, A. B., Venturini, J., Arcaro, S., Montedo, O. R. K., & Bergmann, C. P. (2021). Ballistic ceramics and analysis of their mechanical properties for armour applications: A review. Ceramics International, 47(7, Part A), 8743-8761. https://doi.org/10.1016/j.ceramint.2020.12.095

Haro Albuja, E., Szpunar, J. A., & Odeshi, A. G. (2016). Ballistic impact response of laminated hybrid materials made of 5086-H32 aluminum alloy, epoxy and Kevlar® fabrics impregnated with shear thickening fluid. Composites Part A: Applied Science and Manufacturing, 87, 54-65. https://doi.org/10.1016/j.compositesa.2016.04.007

Hughes, M. (2015). 4 - Plywood and other veneer-based products. In M. P. Ansell (Ed.), Wood Composites (pp. 69-89). Woodhead Publishing. https://doi.org/10.1016/B978-1-78242-454-3.00004-4

Koene, L., & Broekhuis, F. R. (2017). Bullet penetration into wooden targets. 30th International Symposium on Ballistics, Long Beach, CA, 1905-1916. https://doi.org/10.12783/ballistics2017/16976

Koene, L., & Broekhuis, F. R. (2019). Bullet penetration into medium density fibreboard targets. 31st International Symposium on Ballistics, Hyderabad, India, 1363-1373. https://doi.org/10.12783/ballistics2019/33172

Koene, L., Hermsen, R., & Brouwer, S. D. (2013). Projectile ricochet from wooden targets. In Proceedings - 27th International Symposium on Ballistics, BALLISTICS 2013 (Vol. 2).

Koene, L., & Willemsen, G. (2023). Bullet Penetration into Plywood targets. 33rd International Symposium on Ballistics, Belgium.

Lo Ricco, M. T., Weaver, M. K., Adam Senalik, C., Henjum, J., & Cattelino, J. (2023). Ballistic testing of cross-laminated timber layups to further develop protective panels. 13th World Conference on Timber Engineering, WCTE 2023, 1, 75-83. https://doi.org/10.52202/069179-0010

Majumdar, A., Butola, B. S., & Srivastava, A. (2013). An analysis of deformation and energy absorption modes of shear thickening fluid treated Kevlar fabrics as soft body armour materials. Materials and Design, 51, 148-153. https://doi.org/10.1016/j.matdes.2013.04.016

Melderis, J. (2008a). Ieroču un munīcijas unbūves un darbības principi. https://virsnieki.lv/wp-content/uploads/2022/04/Ierocu-un-municijas-uzbuve-un-darbibas-principi.pdf

Melderis, J. (2008b). Principles of construction and operation of weapons and ammunition. http://virsnieki.lv/wp/wp-content/uploads/2016/03/Iero%C4%8Du-un-mun%C4%ABcijas-uzb%C5%ABve-un-darb%C4%ABbas-principi.pdf

Nardin A., Boström L., & Zaupa F. (2000). The effect of knots on the fracture of wood. In World Conference on Timber Engineering. Whistler Resort.

Reashad Bin Kabir, Engr., & Nasrin Ferdous, Engr. (2013). Kevlar-The Super Tough Fiber. International Journal of Textile Science, 1(6), 78-83. https://doi.org/10.5923/j.textile.20120106.04

Salman, S. D., Leman, Z., Sultan, M. T. H., Ishak, M. R., & Cardona, F. (2016). Ballistic impact response of Kevlar® reinforced thermoplastic composite armors. In 43400 UPM Serdang (Vol. 11, Issue 3). https://doi.org/10.15376/biores.11.3.7282-7295

Sanborn, K. (2018). Exploring cross-laminated timber use for temporary military structures: ballistic considerations. https://smartech.gatech.edu/handle/1853/59910

Sanborn, K., Gentry, T. R., Koch, Z., Valkenburg, A., Conley, C., & Stewart, L. K. (2019). Ballistic performance of cross-laminated timber (CLT). International Journal of Impact Engineering, 128, 11-23. https://doi.org/10.1016/j.ijimpeng.2018.11.007

Sanborn, K., Riser, B., Gentry, R., & Stewart, L. (2018). Ballistic performance of enhanced cross-laminated timber (Eclt). WIT Transactions on the Built Environment, 180, 267-278. https://doi.org/10.2495/SUSI180241

Zhang, X., Sun, H., Xu, G., Duan, Y., Jan, V. den B., Joris, V. A., & Shi, J. (2024). Understanding the Effect of Knots on Mechanical Properties of Chinese Fir under Bending Test by Using X-ray Computed Tomography and Digital Image Correlation. Forests, 15(1). https://doi.org/10.3390/f15010174

About the authors

ELINA BARONE

Researcher, Ph.D. student

Riga Technical University, Faculty of Civil and Mechanical Engineering,
Institute of Civil Engineering

Main research area

Bullet-proof wood-based buildings

Address

Kipsalas street 6A-344, LV-1048, Riga, Latvia
E-mail: elina.barone@rtu.lv

BAIBA GAUJENA

Associate Professor

Riga Technical University, Faculty of Civil and Mechanical Engineering,
Institute of Civil Engineering

Main research area

Sustainable construction, eco-materials, energy efficiency, building structures

Address

Kipsalas street 6A, LV-1048, Riga, Latvia
E-mail: baiba.gaujena@rtu.lv

INGARS GRINEVICS

Bachelor Student

Riga Technical University, Faculty of Civil and Mechanical Engineering,
Institute of Civil Engineering

Main research area

Wood-based buildings; CLT, bullet-proof

Address

Kipsalas street 6A, LV-1048, Riga, Latvia
E-mail: ingars.grinevics@gmail.com

MARTINS VILNITIS

Professor

Riga Technical University, Faculty of Civil and Mechanical Engineering,
Institute of Civil Engineering

Main research area

Sustainable construction

Address

Kipsalas street 6A-344, LV-1048, Riga, Latvia
E-mail: martins.vilnitis@rtu.lv