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CALCULATION METHODOLOGY FOR BULLET-RESISTANT WALL STRUCTURES IN MODULAR BUILDINGS

Summary of the Doctoral Thesis

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RIGA TEHNICAL UNIVERSITY
Faculty of Civil and Mechanical Engineering
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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (PhD), the present Doctoral Thesis has been submitted for defence at the open meeting of the RTU Promotion Council on 19 September 2026, at 14.00 at the Faculty of Civil and Mechanical Engineering of Riga Technical University, Ķīpsalas iela 6a, Room 453.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for review to Riga Technical University for promotion to the scientific degree of Doctor of Science (PhD) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for promotion to a scientific degree.

Elina Barone ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an Introduction, five chapters, Conclusion, 55 figures, and 28 tables; the total number of pages is 114. The Bibliography contains 116 titles.

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GENERAL DESCRIPTION OF THE STUDY

Relevance of the Topic and Problem Statement

The unstable global security environment has created an increasing demand for building solutions capable of protecting against ballistic threats. In this context, modular, rapidly deployable, and transportable residential and non-residential buildings are of relevance. Such structures are critical in situations involving armed conflicts, civil unrest, natural disasters, or long-term quarantine conditions, where temporary accommodation must ensure both life safety and acceptable living conditions, even in remote regions [1]. In cases of war, civil unrest, and natural disasters, people are often forced to remain near national borders under conditions unsuitable for habitation. Temporary accommodation should therefore provide short-term shelter buildings that ensure basic living needs and life safety for their occupants. Ideally, these buildings should be easy to construct, relocatable if necessary, and equipped with ballistic protection. Typically, the external envelope of a building provides protection for occupants and assets inside [2]. However, there is a lack of information and research reporting on the integration of ballistic construction materials into building envelope systems. It may be due to restricted access to information resulting from the field's specificity. Latvia has supplied locally manufactured wooden frame modular houses to Ukraine for families with multiple children who have lost their homes due to war. The area of one house is 55 m^2 and is assembled from two screw-connected sections, allowing relocation if required [3]. These buildings are not equipped with additional armour. It would be beneficial to equip them with a safe room or, at a minimum, install a ballistic wall, thereby ensuring not only physical protection but also psychological comfort for residents. In international operations of this type, protective elements are often transported over long distances, making structural weight a critical factor. The light-weight elements are also relevant in building reconstruction projects where increasing the load on load-bearing structures is unacceptable. Such constraints limit the use of traditional steel or concrete structures. The main challenge is therefore to develop structures with sufficiently low mass for transportation while maintaining adequate strength to minimize ballistic threats [4]. The use of timber structures in building construction is becoming increasingly widespread, applied both in new construction and in the modernisation of existing buildings. The design of timber frame structures can also be automated, reducing construction time and streamlining the design process [5]. For transportable modular buildings, timber is selected as the structural frame material due to its relatively low weight, availability, and ease of replacement of individual elements. Consequently, the topic of modular and temporary buildings intended for occupants undergoing short- or long-term quarantine is particularly relevant. Such buildings should be easily transportable and assembleable, thereby reducing transportation costs, and also be rapidly deployable in response to urgent shelter needs, which may significantly affect human health and survival. Bullet-resistant wall structures are commonly installed in public buildings such as banks, armories, shooting ranges, embassies, military facilities, police stations, temporary detention cells (where acoustic insulation, fire resistance, and ballistic protection are critical), hotels, hospitals, and prisons. Regulation (EU) No. 305/2011 of the European Parliament [6]. and of the Council establishes essential requirements for buildings, including user safety. It would also be prudent to implement ballistic-safe walls in schools, as school terrorist attacks have occurred in nearby countries such as Estonia and Finland. In 2014, a student in Viljandi, Estonia, fatally shot a teacher during a weekday afternoon [7].

The relevance of the topic is further intensified by war and interstate conflicts, as well as natural and human-induced disasters (e.g., the destruction of hydroelectric dams), which generate widespread public concern. One method of reducing anxiety is global and individual preventive protection; however, this may simultaneously introduce additional risks, such as the fact that in some countries the number of firearm licenses exceeds the population size. Terrorist incidents not only endanger human safety but may also have long-term consequences for future generations, including impacts on ecosystems and infrastructure. In recent years, financial resources and investments in the defence sector have increased significantly worldwide. Ballistic protection remains one of the most important research and development fields in both civil and military domains. The proper design of protective buildings and structures is complex due to numerous technical requirements. Regardless of the intended service life, a unique parameter in the construction of military facilities is the specification for force protection – the ability of a structure to ensure safety and protection, as well as to maintain normal operating conditions for occupants and equipment within the building [8]–[10]. For bullet-resistant buildings, wall reinforcement is essential. Traditional blast-resistant walls typically use high-strength concrete or steel plates. These materials are complex to make, costly, and significantly increase structural weight. Additionally, structural damage often requires substantial repair time [11]. This study proposes the use of timber materials, whose density is up to five times lower than concrete's density. Under ballistic impact, timber exhibits high mechanical resistance without immediate failure, large deformations, or extensive cracking. Another relatively lightweight material is ultra-high-molecular-weight polyethylene (UHMWPE), combined with laminated plywood. This combination has not yet been widely used as a composite material, generating scientific interest in new applications; however, it is available commercially, also for ballistic protection. Panel joints represent weak points under ballistic threats. Construction works such as electrical installations, plumbing, and ventilation openings may reduce the effectiveness of bullet-resistant walls. Previous studies by RTU Professor A. Borodiņecs and his research group have investigated bullet resistance and microclimate in non-classified buildings [10]–[16], as well as the influence of ventilation channels inside panels on wall ballistics [9]. Since the development of firearms, humans have sought ways to protect themselves from bullets using various obstacles. Initially, readily available materials were used; notably, water-filled bottles and stacks of wet newspapers [17], [18] were once recommended as bullet-resistant barriers. Overall, significant advances have been made in ballistic protective materials [18], [19]. One of the most advanced wood-based materials is nanocellulose, which has also been attributed with special ballistic properties [20].

To date, there are no widely available scientific studies on structurally optimal solutions for prefabricated wood composite panels in transportable buildings subjected to extreme impact loads, nor is the methodology for such studies disclosed. Development in this research direction could significantly contribute to both theoretical terminal ballistics and practical solutions, promoting scientific and market development in ballistic protection. Application of the methodology would allow more accurate models and theories to be developed, improving ballistic experiment simulations. New practical solutions in ballistic wall models would enable new protection approaches and provide higher levels of protection in existing military and civil defence structures.

Aim of the Doctoral Thesis

The Doctoral Thesis aims to develop a calculation methodology for predicting the ballistic resistance of modular wall structures made of timber-based materials for protection classes BR1 and BR2 in accordance with standard EN 1063.

Objectives of the Doctoral Thesis

To achieve the aim, the author defined the following objectives.

1. To conduct a theoretical review of the literature in the field of ballistics.
2. Establish a theoretical and experimental basis for the methodology.
   a) Conduct initial ballistic tests of timber and draw conclusions to ensure the successful continuation of the experimental program.
   b) Carry out studies on the ballistic resistance of timber materials – CLT and plywood. Implement CLT panel tests in a mathematical model using the finite element method.
   c) Determine the apparent dynamic strength of the target material for CLT and plywood for each protection class, enabling calculation of the maximum bullet penetration depth (i.e., the minimum wall thickness) for another weapon using the Poncelet formula, with bullet mass up to 8.0 g and muzzle velocity up to 400 m/s, while establishing a trend for weapons with bullet mass up to 15.6 g and muzzle velocity up to 440 m/s.
3. To develop a methodology suited explicitly for predicting the ballistic resistance of glued timber wall structures for protection classes BR1 and BR2, with trend estimation for BR3 and BR4 according to EN 1063.
4. Validate the developed methodology by creating a practical example demonstrating the transition of bullet penetration depth from BR2 to BR4 class.
5. Expand the research to include the ballistics of multilayer walls.
   a) Adapt the calculation methodology for multilayer CLT walls with thermal insulation and knitted aramid fibre fabric, and for plywood-UHMWPE walls, using the experimental data obtained.
   b) Compare the most promising ballistic wall structures for buildings, considering not only bullet resistance but also wall weight, cost, and thermal resistance as key factors.
6. To develop proposals for the practical implementation of the methodology and for supplementing regulatory documents on timber ballistics.

Scientific Novelty of the Study

The following contributions define the scientific novelty of the Doctoral Thesis.

1. A new calculation methodology has been developed for predicting the ballistic resistance of modular timber wall structures for protection classes BR1 and BR2 in accordance with EN 1063.
2. Material-dependent empirical parameters have been determined for cross-laminated timber (CLT) and plywood, enabling the prediction of average bullet penetration depth and the corresponding minimum required wall thickness for small-arms projectiles with bullet masses up to 15.6 g and velocities up to 440 m/s, covering protection classes from BR1 to BR4.

3. In contrast to existing ballistic prediction approaches, the proposed methodology is relatively simple and adapted explicitly to glued timber-based materials, making it suitable for practical engineering applications.
4. The developed methodology has been experimentally validated, demonstrating sufficient accuracy for engineering-level prediction of ballistic wall performance without the need for full-scale testing.

The novelty of the research is further supported by its practical applicability, dissemination of results through scientific publications and international conferences, and collaboration with stakeholders in the timber construction sector.

Methodological Framework of the Research

The research fields represented in the Doctoral Thesis include ballistics, civil engineering and materials science, mechanics (impact dynamics and numerical modelling), and safety and defence.

The methodology of the study consists of a literature review and analysis of the formulas presented therein, and investigation and calculation of the theoretical penetration depth. In contrast, the experimental penetration depth is obtained through ballistic simulations and tests. The methodology is schematically illustrated in Fig. 1.

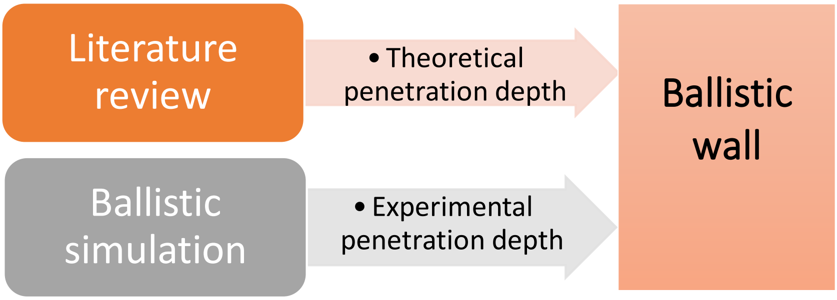


Fig. 1. Scheme of the research methodology.

Practical Significance of the Doctoral Thesis

The methodology developed and validated in this Doctoral Thesis enables accurate prediction of the required timber wall thickness without the need to conduct full-scale experimental testing. This approach reduces financial costs, minimises risk-related aspects, and accelerates the building design process.

In the practical part of the methodology, calculations are performed using experimentally determined material parameters. The BR2 protection class is selected as the experimental reference level, based on which predictions are extended to other protection classes by considering the impact kinetic energy specific to each class, as defined by standardised bullet mass and maximum initial velocity values.

The obtained calculation results are compared with experimental data to validate the accuracy of the methodology. The comparison demonstrates that the proposed methodology enables reliable prediction of the glued timber wall thickness for protection classes BR1 and BR2 in accordance with EN 1063. For these classes, material-dependent parameters have been determined, thereby extending the ballistic property database for spruce cross-laminated timber (CLT) and birch plywood with new empirical data.

The newly developed calculation methodology provides a significant contribution to the field of sustainable construction by offering greater clarity regarding the application of timber materials to ensure the ballistic performance of building wall systems. The advancement of terminal ballistics as a research field may promote progress in both theoretical science and practical engineering solutions, strengthening the interaction between scientific research and market implementation. Further development of the field could enable the formulation of more accurate models and theories, improving the simulation of ballistic experiments. Practical solutions derived from ballistic wall models may facilitate new protection concepts and provide higher levels of protection in existing military and civil defence structures.

Tools and Equipment Used

The handheld firearms used in the experiments were the semi-automatic pistols CZ 75 (manufactured by ČZUB, Czech Republic) and Glock 17 (Austria, Glock series). The ammunition used was 9 × 19 mm Parabellum FMJ (full-metal-jacket) cartridges. At the moment of firing, these firearms generate a noise level of approximately 157–162 dB; therefore, hearing protection devices, including earmuffs and, where necessary, additional earplugs, were an essential part of the occupational safety equipment. The shooting angle (defined as the angle between the projectile axis and the surface of the target) was 90 degrees. Minor deviations were possible since the shooter was a professional human operator rather than a specialised mechanical firing device. In this doctoral study, the experimental scope is limited to Parabellum ammunition with an ogive-shaped projectile. The selection of the firearms and their parameters is justified by the fact that the CZ 75 and Glock 17 represent standardised low-to-medium kinetic energy sources. Their use reduces the number of experimental variables, ensures measurement repeatability, and reflects conditions typical of an urban environment, thereby increasing the relevance of the experiments to real-life scenarios.

Bullet velocity measurements were carried out using two Slingshot Speed Tester chronograph devices manufactured by N/P, with a measurement error of ≤1 % and a precision of ±0.1 m/s. (Standard EN 1063 does not require velocity measurement accuracy better than 1 m/s.) The chronographs were positioned before and after the target material, as close as possible to the wall specimen.

The experimental setup is schematically illustrated in Fig. 2. The bullet flight distance of 8–9 meters correspond to the distance from the firearm muzzle to the specimen in cases of bullet arrest, or to the ballistic block (bullet trap) in cases of complete penetration.

Penetration depths were measured using a steel wire and a hand ruler, with a measurement uncertainty of ±1 mm (corresponding to the smallest scale division), measured up to the rear end of the projectile.

For the CLT and plywood experiments, the velocity of bullets fired from the CZ 75 pistol before to entering the specimen ranged from 327.3 m/s to 345.8 m/s. These values comply with NIJ Standard 0108.01, which specifies an initial velocity of 332 ± 12 m/s for 9 mm projectiles, but do not correspond to the velocity ranges given in Table 1.2 of EN 1063, where values range from 360 ± 10 m/s to 440 ± 10 m/s. Bullet velocity was measured at a firing distance of 8–9 meters from the firearm, immediately before penetration of the target material. According to physical principles, the reduction in projectile velocity over 8–9 meters is negligible. Therefore, the velocity recorded immediately before the target material can be assumed to be equal to the initial muzzle velocity. Minor deviations may result from variations in the propellant charge of the cartridge and the selection of firearm type, which were of random nature in these tests. The U.S. regulatory document NIJ Standard 0108.01 provides more detailed information on the suitability of firearms for specific protection classes, including parameters related to barrel length.

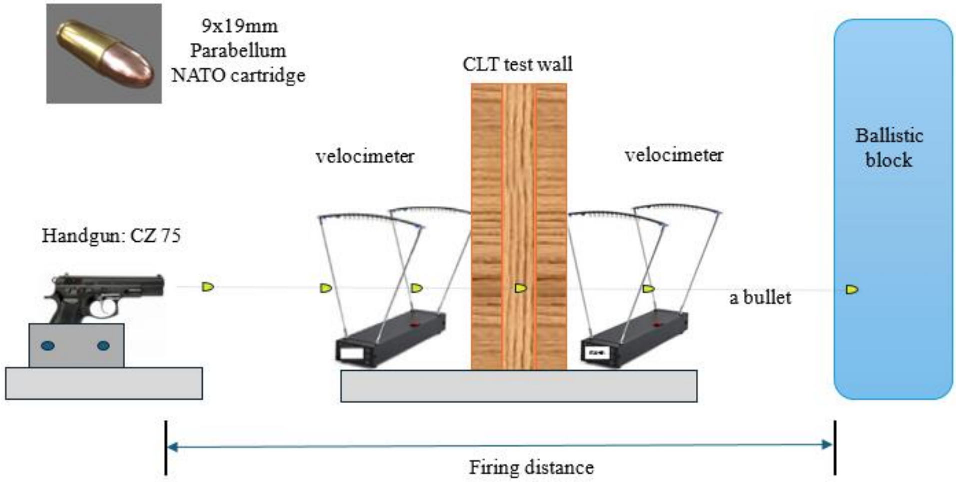


Fig. 2. Configuration of the ballistic workbench.

To improve language clarity and revise selected sentences, the artificial intelligence language model ChatGPT (OpenAI, GPT-5 version, 2025) was used. The model was not employed to generate new scientific conclusions but solely to enhance the stylistic quality and linguistic accuracy of the text. The author has verified all content and assumes full responsibility for its accuracy. The Doctoral Thesis summary was translated using the AI tool ChatGPT.

Limitations of the Study

The proposed methodology applies to protection classes BR1 and BR2, which define an initial projectile velocity range of 330 m/s to 400 m/s and a projectile mass range of 2.5 g to 8.0 g, with an indicated trend extending to 450 m/s and 15.7 g, respectively.

The present study was limited to two handheld firearms and a single type of ammunition corresponding to protection class BR2 in accordance with EN 1063 and EN 10522/10523, using Parabellum cartridges with ogive-shaped projectiles. This limitation was primarily determined by market availability and the frequent use of such ammunition in the relevant field.

The methodology's applicability has not been experimentally verified for other wood species and has been evaluated only for birch plywood and spruce cross-laminated timber.

The proposed methodology does not account for several influencing variables, including the effects of impact angle and firing distance, which may affect the reliability and practical applicability of the results. The study does not consider wall panel fastening and assembly details or their associated costs, nor does it address the variability of joints – identified as the weakest structural elements – and their influence on ballistic resistance. Furthermore, sudden changes in projectile velocity due to random obstacles along the projectile path, variations in projectile dimensions and terminal geometry, the possibility of ricochet, and fragment dispersion are not included. During the experiments, the indoor ambient temperature varied randomly, ranging from +6–7 °C in January to +19 °C in May, whereas the standard specifies an indoor testing temperature of +18 ± 5 °C.

To simplify the calculations, the following assumptions were adopted: the projectile does not deform upon penetration into the material; the kinetic energy of the projectile is fully expended on deformation of the target material; among the many factors influencing penetration capability, the most significant are: a) projectile mass, impact velocity, and projectile nose geometry; b) the resistance characteristics of the target material [21].

Theses Submitted for Defence

- A calculation methodology has been developed to predict the ballistic resistance of modular wall structures for protection classes BR1 and BR2, in accordance with EN 1063. The proposed methodology enables high-accuracy prediction of the required timber wall thickness without conducting full-scale experimental testing, thereby reducing financial costs, safety risks, and the design time of bullet-resistant buildings.
- Empirical parameters, defined as the apparent dynamic resistance R_t, have been determined for cross-laminated timber (CLT), enabling prediction of the maximum penetration depth, or the minimum required wall thickness, under varying projectile velocities (330–400 m/s) and projectile masses (2.5–8.0 g) within protection classes BR1 and BR2. A graphical trend illustrating the performance of higher-powered firearms for protection classes BR3 and BR4 is also presented.
- Empirical parameters have been determined for plywood materials, enabling prediction of the maximum penetration depth, or the minimum required wall thickness, under varying projectile velocities (330–400 m/s) and projectile masses (2.5–8.0 g) within protection classes BR1 and BR2. A graphical trend illustrating the performance of higher-powered firearms for protection classes BR3 and BR4 is also presented.

Structure of the Doctoral Thesis

The Doctoral Thesis consists of five chapters: Literature Review*,* Theoretical and Experimental Background of the Research*,* Methodology for the Evaluation of Ballistic Resistance*,* Experiments for Methodology Validation*,* and Studies on the Ballistics of Multilayer Wall Systems.

During the Doctoral Thesis development, an extensive analysis of scientific studies and information sources on ballistics and commonly used ballistic materials was conducted. This includes an assessment of wood hardness measured by the Janka hardness test, which correlates with the material's resistance to impact loading. An overview of firearm and calibre classifications is provided, and various ballistic-related standards are analysed and briefly compared. The literature review includes essential information on protection classes, the influence of projectile nose geometry on target response, the possibility of ricochet, projectile behaviour within target materials, projectile penetration capability and associated calculation formulas, as well as the influence of adhesive layers on ballistic performance.

In the chapter addressing the theoretical and experimental background of the research, methodologies applied in other successful scientific studies are reviewed and compared, and preliminary ballistic tests on timber materials are analysed. The chapter on the methodology for evaluating ballistic resistance presents procedures for predicting the ballistic resistance of glued timber wall structures for protection classes BR1 and BR2, with trend estimation for protection classes BR3 and BR4, in accordance with EN 1063.

The experiments conducted for methodology validation demonstrate its consistency and include studies on CLT and plywood models aimed at identifying the optimal solution for a BR2-class ballistic wall, and numerical modelling using the finite element method. The thesis also includes an analysis of parameter optimisation.

The research is further extended by studies on the ballistics of multilayer wall systems, examining the behaviour of CLT and plywood in layered configurations. In addition, a comparison of 10 ballistic wall structures is conducted to categorise both previously known and author-investigated ballistic barriers based on their performance limits. Proposals for the practical implementation of the methodology and for supplementing regulatory documents on timber ballistics are also being developed.

The Doctoral Thesis concludes with a summary of the main findings.

The Thesis is 115 pages long and includes 52 figures, 28 tables, and 55 formulas. A total of 116 literature sources were used. The Doctoral Thesis is written in Latvian.

Validation and Dissemination of the Doctoral Thesis Results

The results of the Doctoral Thesis have been presented and discussed at three international conferences:

1. **Barone**, **E**., Vetra, R., Gaujena, B., Vilnitis, M. Ordinary gypsum plasterboard, and Knauf Torro gypsum plasterboard bullet-proofing. RTU IMST, Sept 28–30, 2022, Riga, Latvia https://imst.rtu.lv/wp-content/uploads/sites/59/2022/12/IMST-PROGRAMMA-2022-web-1-1.pdf (author's contribution 70 %)
2. **Barone**, **E**., Gaujena, B., Vilnitis, M. Literature Review of Applicable Ballistic Materials for Temporary Wooden Building Envelopes, 30th International Baltic Conference, Materials Engineering and Modern Manufacturing, Oct 19–20, 2023, Kaunas, Lithuania (author's contribution 80 %)
3. **Barone**, **E**., Hamenoks, D., Gaujena, B., Vilnitis, M. Plywood wall for bulletproof modular buildings. RTU IMST, Sept 10–12, 2025, Riga, Latvia (author's contribution 80 %)

List of Scientific Publications

1. Borodinecs, A., Geikins, A., **Barone**, **E**., Jacnevs, V., Prozuments, A. Solution of Bullet Proof Wooden Frame Construction Panel with a Built-In Air Duct. Buildings, 2022, Vol. 12, No. 1, Article number 30. ISSN 2075-5309.
   Available from: doi:10.3390/buildings12010030 (Author's contribution 10 %)

2. **Barone**, **E**., Vetra, R., Gaujena, B., & Vilnitis, M. Ordinary gypsum plasterboard and Knauf Torro gypsum plasterboard bullet-proofing. The Journal of Physics: Conference Series, 2423(1), 2023, doi:10.1088/1742-6596/2423/1/012016
Available from: https://iopscience.iop.org/article/10.1088/1742-6596/2423/1/012016
(Author's contribution 70 %)
3. **Barone**, **E**., Velicko, E., Gaujena, B., Vilnitis, M. Plywood Panel with UHMW Polyethylene Board Ballistic Resistance. Journal of Sustainable Architecture and Civil Engineering, 2023, Vol. 32, No. 1, pp. 233–243. ISSN 2029-9990. e-ISSN 2335-2000.
Available from: doi:10.5755/j01.sace.32.1.32822. (Author's contribution 80 %)
4. **Barone**, **E**., Gaujena, B., Vilnitis, M. Literature Review of Applicable Ballistic Materials for Temporary Wooden Building Envelopes, Advances in Science and Technology, 2023, 134 AST, pp. 29–40 Available from: doi:10.4028/p-9J2iRE (Author's contribution 90 %)
5. **Barone**, **E**., Grinevics, I., Gaujena, B., Vilnitis, M. CLT Wall for Bullet-Safe Temporary Buildings. *Journal of Sustainable Architecture and Civil Engineering*, 2025, Vol. 37, No. 1, pp. 97−108. ISSN 2029-9990. e-ISSN 2335-2000.
Available from: doi:10.5755/j01.sace.37.1.38395 (Author's contribution 70 %)
6. **Barone, E.,** Gaujena, B., Videmanis, J. Projectile Penetration Depth into Wood-Based Frame of Unclassified Buildings. *Far East Journal of Mechanical Engineering and Physics*, 2022, Vol. 3, pp. 11−20. e-ISSN 2229-4511.
Available from: doi:10.17654/2229451122002 (Author's contribution 70 %)

CONTENT OF DOCTORAL THESIS

1. LITERATURE REVIEW

For security and defence concerns, bullet-resistant building wall structures serve as both a physical and psychological shield. Literature analysis indicates that timber has both advantages and limitations compared with commonly used protective materials such as steel and concrete, while glued timber technology enhances hardness and impact resistance. Ballistics studies the behaviour of projectiles during flight. The term *"bulletproof"* is relatively misleading, as no material is completely impenetrable. Ballistics is divided into three scientific branches [8], [22]: internal ballistics, external ballistics, and terminal ballistics – the latter studies the behaviour of a projectile and its effects after impact with the target [8]. Due to the wide variation in firearm dimensions and masses, as well as the different diameters, shapes, and muzzle velocities of projectiles − ranging from 360 m/s to 820 m/s − the scope of the research must be clearly limited, and experimental boundaries must be defined. In addition, experimental results are influenced by the projectile impact angle and potential sources of uncertainty, such as ricochet and air resistance. The following standards and regulatory documents fully or partially define testing conditions: EN 1063; EN 1522 / DIN EN 1522; EN 1523 / DIN EN 1523; BS 5051; UL 752; ASTM F1233-08; NIJ Standard 0108.01; and the UFC 4-023-07 document.

As the primary reference for protection levels in the Doctoral Thesis, the standard EN 1063 "Standards for ballistic-resistant protective materials" has been adopted. This standard, developed by the European Committee for Standardisation, is intended for the assessment of bullet-resistant glazing, and is commonly used in conjunction with EN 1522. The standards classify material resistance into protection classes corresponding to specific firearm types and ammunition and define the associated testing conditions. Although EN 1063 is primarily intended for bullet-resistant glass, which differs significantly from timber and other materials investigated in this study, it remains one of the few publicly available documents applicable within the European regulatory framework. Therefore, it can serve as a methodological basis for developing ballistic resistance classification principles for other construction materials [23].

Table 1.1

Classification of Firearm Ballistic Resistance Classes According to EN 1063 Table 1

Class EN 1063	Type	Calibre	Cartridge type	Mass (g)	Conditions	
					Distance (m)	**Bullet velocity (m/s)**
BR1	rifle	22 LR	L/RN	2.6 ± 0.1	10 ± 0.5	360 ± 10
BR2	handgun	9 mm Luger	(1) FJ/RN/SC	8.0 ± 0.1	5 ± 0.5	400 ± 10
BR3	handgun	357 Magnum	(1) FJ/CB/SC	10.2 ± 0.1	5 ± 0.5	430 ± 10
BR4	handgun	357 Magnum	(1) FJ/CB/SC	10.2 ± 0.1	5 ± 0.5	430 ± 10
	handgun	44 Rem. Mag.	(2) FJ/FN/SC	15.6 ± 0.1	5 ± 0.5	440 ± 10
BR5	rifle	5.56 × 45	(2) FJ PB/SCP1	4.0 ± 0.1	10 ± 0.5	950 ± 10
BR6	rifle	5.56 × 45	(2) FJ PB/SCP1	4.0 ± 0.1	10 ± 0.5	950 ± 10
	rifle	7.62 × 51	(1) FJ/PB/SC	9.5 ± 0.1	10 ± 0.5	830 ± 10
BR7	rifle	7.62 × 51	(2) FJ/PB/HC1	9.8 ± 0.1	10 ± 0.5	820 ± 10

According to the magnitude of the firearms impact, they are classified. In standard EN 1063, as well as in DIN EN 1522/1523, protection classes ranging from BR1 to BR7 are defined. (Table 1.1) A higher protection class imposes more stringent structural requirements on the target, and the numerical designation of protection classes corresponds to increasing ballistic resistance. If a specimen meets the requirements of a given class, it is also considered to comply with all preceding lower classes. The first four classes, BR1–BR4, correspond to handguns, sporting rifles, and revolvers capable of imparting initial projectile velocities ranging from 360 m/s to 440 m/s, which exceeds 1500 km/h. These classes differ primarily in the calibre of the wall or target structure that they can withstand. Protection classes BR5–BR7 correspond to rifles, which are high-powered firearms, such as the American M16 or NATO-standard G36 and G3 rifles. These weapons impart projectile velocities ranging from 820 m/s to 950 m/s, exceeding 3000 km/h. Such firearms are effective and accurate at long distances. Standard EN 1063 defines the testing procedure. The test temperature matches the conditioning environment's temperature range. The target material dimensions are (500 ± 5) mm × (500 ± 5) mm, and projectiles are aimed at the vertices of an equilateral triangle with a spacing of 120 ± 1 mm between impact points, to avoid mutual influence of the impacts. The test is conducted using an automatic rifle.

To stop a high-velocity projectile, a protective shield or barrier made of a material capable of receiving and absorbing a large amount of kinetic energy is required. The interaction of a projectile with a material (i.e., its inertial force [24]) depends on the characteristics of the projectile and the properties of the target material, including structural complexity, layering, the woven or knitted fibres, density, hardness, and resistance under high-impact loading. Cross-laminated timber (CLT) and plywood are manufactured by crosswise bonding multiple thinner wood layers perpendicular to each other, thereby preserving the favourable properties of timber while improving its weaker characteristics – such as resistance to cracking, overall strength, and reduced anisotropy. Adhesives ensure bonding between layers and influence not only the mechanical properties but also the ballistic performance of the final composite material. The ballistic behaviour of adhesives depends on their energy absorption capacity, interlayer adhesion, and their plasticity and deformation capability. Although the adhesive is not the primary factor in predicting ballistic resistance, it directly affects timber's mechanical properties, which correlate with resistance to projectile impact [65], [66].

Despite centuries of research, the ballistic resistance of wood remains insufficiently resolved [25]. Timber targets are widely used in explosive testing to ensure safety and standardisation during experimental procedures. [24] However, in standard protective models, the required thickness of wood for stopping a projectile is often overestimated. [25] The penetration depth in timber materials is related to the wood's physical properties. [26], [27] Imperfections in timber materials, such as anisotropy, affect their mechanical properties, including the interaction with a projectile. Projectile behaviour in timber can at times be unpredictable, as wood contains a relatively high number of visible and hidden knots, which reduce the predictability of its strength and resistance [26], [28]–[30], particularly in spruce and pine species [26]. The properties of CLT composite materials, combined with the energy-absorption capacity of timber panels, offer a promising direction for their application in military structures. The advantages of CLT materials: good thermal insulation performance, sound insulation, relatively low material weight, and panels that are quick and easy to assemble, suitable for both interior and exterior finishing, and exhibit increased resistance to rodents due to the perpendicular orientation of wood fibres. Timber remains insufficiently assessed for blast protection due to its lower strength than steel and concrete. [8]

Calculations based on penetration formulas date back to the 18th century. Among the most well-known and widely applied are the de Marre, Euler-Robins, Poncelet, and Resal formulas. The derivation and calibration of these formulas are time-consuming and require substantial effort; moreover, their accuracy shows some randomness. Therefore, empirical models [30] provide an efficient and rapid approach to result analysis. The Poncelet formula is a convenient approach for calculating projectile penetration depth. It includes a parameter that depends on the properties of the target material, which are either not available or only partially documented in the scientific literature. Consequently, the formula is not complete and does not allow direct calculation of penetration depth for layered materials, including CLT. Therefore, further extensions are required, or these material-dependent parameters must be determined for the target materials.

The Poncelet model (Equations 1.1 and 1.2) implies the resistance of wood to projectile penetration can be described by physically interpretable components. [8], [26], [31], [32].

$$\boldsymbol{m_p \frac{dv}{dt} = F = -\beta - \alpha v^2}, \tag{1.1}$$

where m_p is the mass of the projectile, kg; v is initial impact velocity at time t, m/s; β is a parameter dominated by the strength of the material, (kg · m)/s^2; α is represents the coefficient of internal material stresses, equal to the product of the target density, the projectile shape coefficient, and the projectile cross-sectional area, kg/m; and F is force by which the projectile overcomes the penetration distance, N.

In the Poncelet equation, it is assumed that the projectile, does not undergo significant mass loss during its motion; therefore, m=const. This assumption is not always accurate, as during impact the projectile may undergo expansion, mushrooming, fragmentation, or complete disintegration. The penetration depth P of the projectile depends on the deceleration of the projectile within the target and on the projectile velocity. The integral of Equation (1.2) yields the resulting penetration length P as a function of the initial impact velocity (v_i):

$$\boldsymbol{P = \frac{m_p}{2\alpha} \ln\left(1 + \frac{\alpha v_i^2}{\beta}\right)}. \tag{1.2}$$

The experimental data on projectile penetration depth were analysed using the Poncelet model, which is largely based on Newton's second law, F = m×a. The apparent dynamic strength of the target material is calculated using the following formula:

$$\boldsymbol{R_t = \frac{\beta}{A}}, \tag{1.3}$$

where A is the frontal area of the projectile. The apparent dynamic strength correlates with the shear strength of the target material and its Janka hardness. [26], [28], [33], [34].

Research on the ballistics of timber materials has also been conducted in the United States, for example, by K. Sanborn and Marco T. Lo Ricco, in the Netherlands by L. Koene, F., etc. This study selects timber as a sustainable target material because of its not-yet-fully-explored ballistic properties. The BR2 protection class is chosen as it reflects practical civil-use scenarios and enables controlled, repeatable experiments using accessible facilities, ensuring comparability of results and methodological transparency.

These achievements provide the theoretical and experimental basis for developing a methodology to determine the minimum wall thickness for glued timber elements. In the research reports of other scientists (Dr. K. Sanborn, Marco T. Lo Ricco, L. Koene, F. Broekhuis,

G. Willemsen), it is shown that an experimental approach and data analysis with precise measurement control and validation of theoretical models were employed. The studies differ in terms of the materials and equipment used, testing approaches, measurement techniques, data analysis methods, and validation of theoretical models. Their common feature is experimental firing at the target material and subsequent data processing. For example, the methodology developed by L. Koene and colleagues is based on an experimental approach with quantitative data analysis, using physical and mechanical models.

However, these studies do not address: the specific characteristics of glued structural elements for BR1–BR4 protection class projectiles developed in accordance with European standards such as EN 1063 and the NIJ 0108.01 standard. The ballistic response of materials with varying thicknesses was investigated. All studies included projectile velocity reduction and energy absorption capacity. An empirical and theoretical linkage with the Poncelet model was established. Experimental results of CLT panels were used for validation and optimisation of the Poncelet formula, determining the apparent dynamic strength of CLT material using an empirical method. This approach was not applied in previous studies, which predominantly used the model theoretically without determining locally obtained parameters. Numerical modelling using the finite element method was included; in other studies (particularly those by Sanborn and Lo Ricco), this was addressed only conceptually; parameter optimisation analysis was incorporated. Integration with additional materials (Kevlar and mineral wool, UHMWPE). The results of the theoretical and experimental studies confirm the need for a new scientific methodology for determine the ballistic resistance of glued wooden wall structures. To date, no such studies have been conducted in Latvia.

The need for a new methodology is further demonstrated by the lack of experimental - theoretical comparison. Previous studies have employed theoretical models such as the Poncelet and Euler–Robins formulas; however, their validation against experimental results is insufficient. Not all model parameters, such as the apparent dynamic strength, have been identified, which would allow for a more accurate determination of the projectile penetration depth. Studies on the ballistic resistance of wood also lack sections on optimisation and numerical modelling using the finite-element method. Moreover, not all scientific works mention that the protection class could be improved by incorporating additional materials such as aramid or high-density polyethylene, nor do they address the influence of thermal insulation on enhancing ballistic performance. The results of the initial ballistic experiments demonstrate that ballistic resistance depends on the material type, moisture content, and layer thickness. Therefore, a methodology is required to determinate the optimal wall thickness for different protection classes, in accordance with EN 1063.

The conclusion drawn from this is that the development of a new theoretical and experimental methodology would provide a scientifically grounded approach for evaluating the ballistic resistance of glued wooden structures, contributing to the advancement of both ballistic material science, and building science. Accordingly, the proposed methodology is distinguished by the following features: linkage of experimental testing with European standards, ballistic analysis of materials with varying thicknesses, validation of results using finite element software, and parameter optimisation.

2. THEORETICAL AND EXPERIMENTAL BACKGROUND OF THE RESEARCH

2.1. Initial Ballistic Testing of Timber

At the initial stage of the research, the impact of projectiles on timber panel products suitable for modular buildings located in ballistically sensitive areas (army headquarters, barracks, refugee shelters) was examined. The ballistic resistance of timber materials was tested, specifically the penetration depth in spruce cross-laminated timber (CLT) and birch plywood samples of various thicknesses.

The Poncelet model was used for the theoretical calculation of bullet penetration, as it corresponds well with the experimental results. Based on the experimental findings, the use of an 84 mm plywood panel and a combined panel is recommended for building walls, whereas the other tested materials – CLT up to 120 mm thick and plywood thinner than 84 mm - are not recommended. It was confirmed that the selection of test specimen/wall thickness must be based on theoretical calculations. The experiment evaluated the ballistic resistance (penetration depth) of various timber products:

- CLT material samples were manufactured locally by SIA Profi (Latvia). The moisture content was 12 ± 2%. Spruce, strength class C24.
- Plywood samples were produced from LF-CPR/CE-DoP-01 – Riga® birch plywood (JSC Latvijas Finieris), without surface coating, bonded with phenol-formaldehyde adhesive. Its application is in load-bearing structural elements. These materials were selected due to their widespread use in the Nordic region. The direction of wood fibres was not considered.

In the first experiment, a BR2 protection class weapon was used – a Glock 17 pistol with 9 × 19 mm fully metal jacket (FMJ) ammunition, characterised by stable flight. The thicknesses and number of layers of the CLT samples are presented in Table 2.1.

Table 2.1

Layers and Thicknesses of CLT Samples

Sample	Material	Thickness, mm	Layers	Glue type
C60	spruce CLT	60	20-20-20 mm	urea-formaldehyde (UF)
C80	spruce CLT	80	30-20-30 mm	
C100	spruce CLT	100	20-20-20-20-20 mm	
C130	spruce CLT	130	30-20-30-20-30 mm	
P1	birch plywood	28	19	phenol-formaldehyde (PF)
P2	birch plywood	56	19 × 2	
P3	birch plywood	84	19 × 3	

The weapons used in the experiment comply with the BR2 security level, which specifies the projectile mass and velocity according to technical requirements. For the Glock 17 pistol, the bullet muzzle velocity is 345 m/s and the bullet mass is 8.0 grams. The shots were fired at a 90° impact angle from 5 meters. The 5-meter firing distance is the testing distance specified in the EN 1063 standard, although it does not always correspond to a real threat scenario. The experiment was conducted at a shooting range in Riga. The indoor air temperature ranged from

+19 °C to +21 °C. Shooting accuracy depended on the professional shooter's ability to replicate a realistic situation.

Only in the three-layer P3 specimen did the Glock 17 bullet stop, embedding between the second and third plywood boards. This behaviour is also influenced by the shear surface resistance. Therefore, the penetration depth P is within the range of 56–84 mm. In the thinner specimens P1 and P2, the bullets fully perforated the panels. The bullets perforated all CLT specimens. Thus, the penetration depth exceeded the 130 mm thickness of the CLT target.

The theoretical values of the penetration depth P were calculated using Equation (1.8) and are presented in Table 2.2 with the given parameters. The weapon used (Glock 17 pistol) has a projectile mass of 8 grams and a projectile velocity of 400 m/s; therefore, the calculated penetration depth is shown in column P and compared with the specimen thickness h.

For spruce CLT, the parameters α and β were taken from [26], based on Douglas fir parameters (α = 0.013 kg/m and β = 2300 kg × m/s²). The theoretical calculation of the penetration depth P for the CLT specimen is as follows:

$$\boldsymbol{P} = \frac{0{,}008kg}{2\times 0{,}0028kg/m}\,\mathbf{ln}\,(\mathbf{1} + \frac{0{,}0028kg/m\times(400m/s)^2}{1500kg*m/s^2}) = 0.198\,m.$$

The penetration depth for birch plywood was obtained by averaging parameters from other hardwood species (a low value of α = 1×10⁻¹³ kg/m and a relatively high value of β = 9000 kg×m/s²). This approach was justified by the fact that the density of Merbau wood indicated in publication [26] is closer to the density of birch.

$$\boldsymbol{P} = \frac{0{,}008kg}{2\times 1\times 10^{-13}kg/m}\,\mathbf{ln}\,(\mathbf{1} + \frac{1\times 10^{-13}kg/m\times(400m/s)^2}{9000kg*m/s^2}) = 0.071\,m.$$

The theoretical calculations (Table 2.2), which were performed after the experimental computations, confirmed the penetration depth results obtained in the practical shooting tests.

Table 2.2

Experimental and Theoretical Calculations of the Penetration depth P

Samples No.	Experimental penetration depth P, m — Thickness of the test specimen, m	Theoretical calculations of the penetration depth P, m — Glock 17 m=8 g v_o=400 m/s
C100	0.100*	0.198
C130	0.130*	
P1	0.027*	0.071
P2	0.056*	
P3	0.084 – stopped between 2nd un 3rd layer	

* The projectile passed through both weapon types

Using the Poncelet model, the calculations showed that the selected material thicknesses were not suitable for bullet resistance. Only the P3 specimen withstood the impact of the Glock 17 (BR2 protection class).

CLT panels up to 130 mm thick and plywood panels thinner than 54 mm are not recommended for ensuring ballistic resistance of walls. In further research, it is recommended to conduct experiments with thicker CLT and plywood wall structures.

2.2. Experimental and Theoretical Justification of the Calculation Methodology

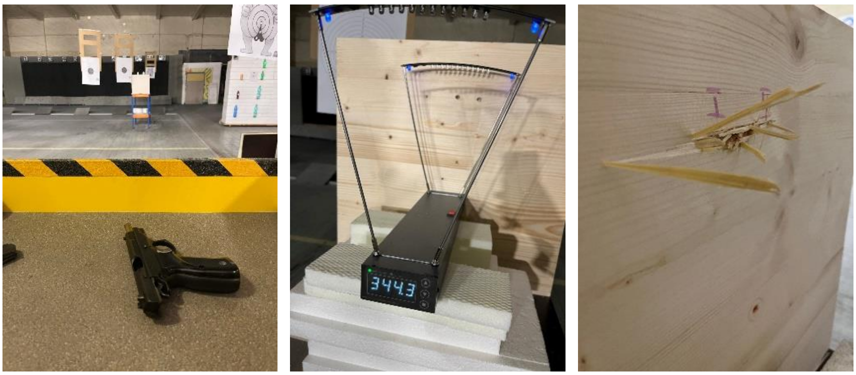
To develop the calculation methodology, and based on the previous research, thicker CLT and birch plywood wall specimens of various thicknesses were tested. The ability of these wood composite materials to absorb the kinetic energy of a projectile was determined, and the minimum wall thickness required to ensure protection in accordance with EN 1063 standard classes BR1 and BR2 was established, while also identifying a projected trend for BR3 and BR4 classes. The specimens were conditioned for two months at 19 °C and 12 % relative humidity, resulting in moisture contents of 5.3 % for CLT and 5.0 % for plywood. These low-moisture conditions represent a worst-case scenario, as reduced moisture increases brittleness and penetration depth. Parameters of the materials used in the tests are summarised in Table 2.3.

Table 2.3

Parameters of the Testing Materials

Material	**Density, kg/m^3**	**Moisture, %**	**Glue type**	**Specimen thickness, mm**
CLT	461.7	5.3	urea formaldehyde	80, 100, 140, 150, 240, 260
Birch plywood	669.9	5.0	phenol formaldehyde	27, 54, 81 (1, 2, 3 layers)

The experimental study was limited to a single handgun (CZ 75, 9 ×19 mm Parabellum FJM, Fig. 2.1 (a)), selected as a standardised low-to-medium kinetic energy source to ensure repeatability and relevance to urban scenarios. Higher-velocity firearms, such as the AK-47, were excluded from further testing, as projectiles exceeding 440 m/s fall outside the defined scope of BR1–BR4 protection classes according to EN 1063.



(a) (b) (c)

Fig. 2.1. CZ 75 weapon was used (a), a velocity measuring velocimeter (b), projectile exit (c).

The specimens were produced in an RTU laboratory and tested at a shooting range under controlled conditions (10.4 °C, 72 % RH), with negligible environmental influence due to short exposure time. Projectile velocities were measured using two chronographs (Fig. 2.1 (b)), and penetration depths were determined with an accuracy of ±1 mm. Tests were conducted at firing distances of 8.3–9.0 m on (500 ± 5) mm × (500 ± 5) mm specimens, corresponding to protection class BR2 according to EN 1063 (Class 1 according to UL 752), with 3–5 shots per wall.

In contrast to other ballistic studies (e.g., M. T. Lo Ricco et al., *"Ballistic testing of cross-laminated timber layups to further develop protective panels"*; L. Koene and F. R. Broekhuis, *"Bullet penetration into wooden targets"*; K. Sanborn et al., *"Ballistic performance of enhanced cross-laminated timber (ECLT)"*), the present experiment employed a quasi-constant projectile impact velocity. The average velocity of projectiles fired from the CZ 75 pistol before entering the specimen was 341.8 m/s, based on five measurements. In the second experimental series, the average projectile velocity before to impact was 339.7 m/s. These values comply with NIJ Standard 0108.01, which specifies an initial velocity of (332 ± 12) m/s for 9 mm projectiles, but do not correspond to the velocity ranges defined in EN 1063 (Table 1.1), where values range from (360 ± 10) m/s to (440 ± 10) m/s.

2.2.1. Experimental and Theoretical Investigation of CLT

A wide practical testing range of CLT wall thicknesses – from 80 mm to 260 mm (see Table 2.4) – was selected as the object of the study. The CLT panels used in the research were manufactured in Latvia. The experimentally determined density of the CLT was 461.7 kg/m³.

Table 2.4

Thickness and Layers of CLT Samples

Sample No.	Thickness, mm	Layers	Glue type
C80	80	30-20-30	urea formaldehyde
C100	100	20-20-20-20-20	
C140	140	40-20-20-20-40	
C150	150	30-30-30-30-30	
C240	240	40-40-20-40-20-40-40	
C260	260	40-40-30-40-30-40-40	

At the initial stage of the study, C80, C100, and C140 specimens were tested. Each specimen was shot through 3–5 times, and the bullet velocities were measured before and after passing through the material. The difference in velocity indicates how many meters per second the material "removes" from the bullet.

- **C140 specimen**: The maximum impact velocity was 345.8 m/s, and the exit velocity was 164.8 m/s; the minimum velocity reduction was 181 m/s.
- **C100 specimen**: The average impact velocity was 339.9 m/s, and the exit velocity was 197.6 m/s; the minimum velocity reduction was 142.3 m/s.
- **C80 specimen**: The maximum impact velocity was 339.9 m/s, and the exit velocity was 252.4 m/s; the minimum velocity reduction was 87.5 m/s.

One approach to interpreting the research results is to assume that the bullet penetration depth is linearly dependent on the material thickness and to calculate the ability of 1 mm of material to reduce the bullet velocity, expressed in meters per second. It should be considered that wood is anisotropic and that CLT is a layered material, including adhesive layers between the CLT boards. The results show that the stopping capacity of 1 millimetre of CLT is at least 1.1 m/s per 1 mm (obtained from the C80 specimen), while the average value is 1.61 m/s per 1 mm. The number of layers in the C140 and C100 specimens does not differ; however, the thickness of the outer layers differs. It can therefore be concluded that the number of layers and their thickness constitute a significant criterion. It is evident that, on average, the bullet velocity is absorbed uniformly within each material, regardless of the number and thickness of layers.

Figure 2.2 shows the ratio of the absorbed velocity difference in CLT material to the initial bullet velocity as a function of material thickness. The blue line represents the trend.

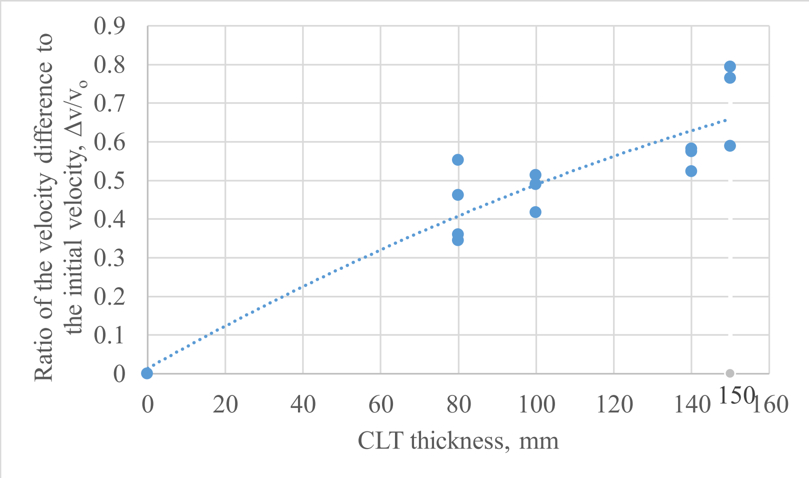


Fig. 2.2. Ratio of the absorbed velocity difference in CLT material to the initial bullet velocity as a function of material thickness. The blue line represents the trend.

When experimentally testing the C240 wall specimen, the maximum bullet penetration depth was 154 mm, while for C260 it was 159 mm. In contrast, for the C150 wall, two bullets fully perforated the wall, whereas three bullets resulted in a maximum penetration depth of 105 mm. These results are consistent with the conclusion regarding the guaranteed CLT thickness that prevents bullet perforation.

Table 2.5 presents a summary of the experimental data, where Δv (m/s) represents the smallest velocity change (energy reduction) achieved by the respective wall.

Table 2.5

Summary of CLT Panel Shooting Results

CLT, mm	Maximum (mean) penetration depth P, mm	Minimum (mean) velocity difference Δv, m/s	Minimum (mean) velocity difference Δv per 1 mm, (m/s)/mm
80	Penetrated	87.5 (128.9)	1.29 (1.611)
100	Penetrated	142.3 (161.0)	1.42 (1.610)
140	Penetrated	181.0 (225.9)	1.09 (1.614)
150	145.0 (105.0)	Projectile stopped	-
240	154.0 (122.5)	Projectile stopped	-
260	159.0 (145.5)	Projectile stopped	-

CLT blocks absorb a certain amount of the bullet's kinetic energy where the experimentally obtained absorbed energy was applied. The amount of kinetic energy as a function of CLT block thickness is shown in Fig. 2.3, assuming a bullet mass of 8 grams. The graph exhibits a nonlinear (curvilinear) trend. Based on such a curve, it is possible to predict the absorbed kinetic energy of CLT material for any given thickness.

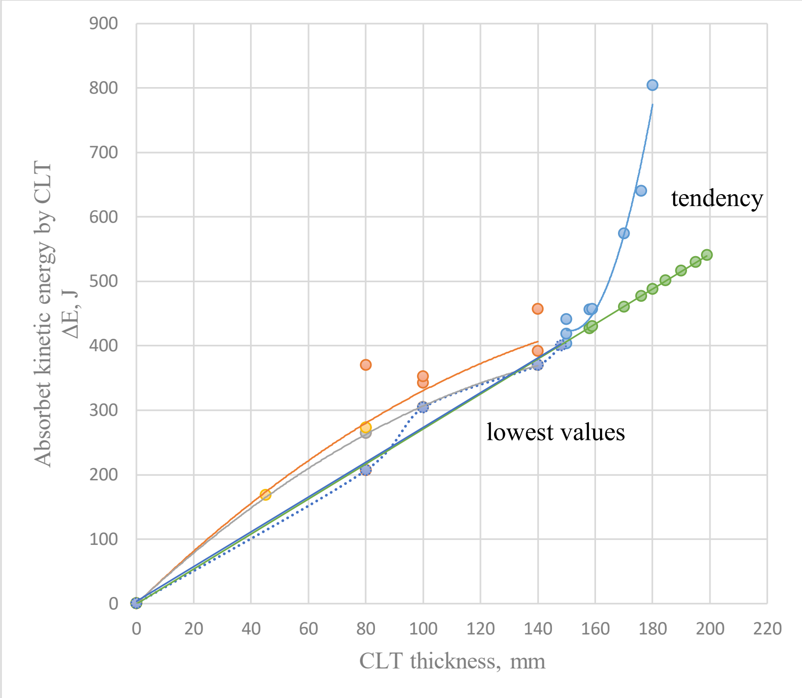


Fig. 2.3. Experimentally determined absorbed projectile kinetic energy of CLT panels as a function of material thickness. Orange points and curve – experimental data. Blue points – minimum values and trend line. Green points – linear trend line.

A thickness of 150 mm could be used as the V50 ballistic limit test point, since C150 was the specimen in which some bullets perforated the panel while others were stopped.

Next, the calculation of the **apparent dynamic strength** R_t or the **BR2 protection class** is presented:

1) Experimentally determine the velocity absorbed by the target

$$\Delta v = v_r - v_o = 345.8 - 164.8 = 181 \text{ m/s (C140)}.$$

2) Experimentally determine the absorbed difference of squared velocities

$$v_r^2 - v_o^2 = 345.8^2 - 164.8^2 = 92418.6 \text{ m}^2/\text{s}^2.$$

3) Using the basic kinetic energy formula (1.53), calculate the energy absorbed by the bullet.

$$E_{kin} = \frac{0.008\text{kg} \times 92418.6 \text{ m}^2/\text{s}^2}{2} = 369.7 \text{ J}.$$

4) Create a graph: absorbed energy as a function of target thickness for BR1 and BR2 protection classes, projecting a trend for protection classes BR3 and BR4. See Fig. 2.3.
5) From the graph, read the thickness of each material (which would be equal to the minimum penetration depth *P*) depending on the energy required for classes BR1–BR4. See Table 2.6. For BR2, *P* = 176 mm.
6) Using the Poncelet formula (1.8), calculate the material strength parameter β. The formula also includes the bullet mass and velocity, and α – the internal stress coefficient

of the material - which is equal to the product of the target density ρ, the bullet shape coefficient C and the bullet cross-sectional area A, in kg/m.

$$\alpha = \rho \times C \times A = \frac{461.7kg}{m^3} \times 0.342 \times 6.36 \times 10^{-5}m^2 = 0.0100kg/m$$

where the bullet area A, m^2 for a 9 mm bullet diameter is:

$$A = \pi \times \frac{d^2}{4} = \pi \times \frac{0{,}009m^2}{4} = 6.36 \times 10^{-5}m^2$$

The material strength parameter β s obtained by expressing it from Formula (1.8):

$$\beta = \frac{\alpha \times v_0^2}{e^{\frac{2 \times P \times \alpha}{m}} - 1} = \frac{0{,}0100kg/m \times (400m/s)^2}{e^{\frac{2 \times 0.176m \times 0.0100kg/m}{0.008kg}} - 1} = 2892\ kg \times m/s^2$$

7) Calculate the apparent dynamic strength Rt, by dividing the material strength parameter β y the bullet cross-sectional area A, formula (1.10).

$$R_t = \frac{\beta}{A} = \frac{2892\ kg \times m/s^2}{6.36 \times 10^{-5}m^2} = 45.48\ MPa$$

The absolute error was calculated from the smallest scale divisions of the involved quantities.

Calculations for the remaining protection classes are shown in Table 2.6.

Table 2.6

Characteristics of the Bullet and Plywood Material for Each Protection Class BR1-BR4

	Characteristics of the bullet						Characteristics of the material					
Protection class	*E*, J	*m*, g	v_0, m/s	*C*	*d*, mm	*A*, mm^2	ρ, kg/m^3	α, kg/m	*P*, mm	β, $kg \times m/s^2$	R_t, MPa	ΔR_t, MPa
BR1	168	2.6	360	0.34	5.7	2.46E-05	461.7	**0.0040**	**60**	2557	**100.24**	5.09
BR2	640	8.0	400	0.342	9.0	6.36E-05	461.7	**0.0100**	**176**	2892	**45.48**	5.22
BR3	943	10.2	430	0.34	9.0	6.36E-05	461.7	**0.0100**	**185**	4241	**66.70**	3.23
BR4	1510	15.6	440	0.30	10.9	9.33E-05	461.7	**0.0127**	**199**	6425	**68.89**	3.15

Based on the obtained data regarding the absorbed kinetic energy for a given CLT material thickness, the minimum required CLT thickness for each protection class (according to EN 1063) was read from the graph in Fig. 2.3 (see Table 2.6). The values for protection classes BR1 to BR4 were 60 mm, 176 mm, 185 mm, and 199 mm, respectively. For safety purposes, the obtained wall thicknesses (i.e., penetration depths) are rounded up to the nearest 1 mm. However, since manufacturers typically provide standard CLT thicknesses, these values would be rounded to the safer side, resulting in 60 mm, 180 mm, and 200 mm.

The parameter α, representing the material internal stress coefficient, ranges from 0.0039 kg/m to 0.0127 kg/m. Using the Poncelet formula, the material strength parameter β was obtained for each protection class. This parameter is not constant, as it depends on the bullet cross-sectional area. The given bullet muzzle velocities and masses are defined according to EN 1063. The initial velocity for the BR2 class differs from the experimentally observed maximum value of 345.1 m/s.

Using Formula (1.10), the apparent dynamic strength R_t, MPa of the material is determined, which is unique for each target material. Empirically obtained apparent dynamic strengths of CLT corresponding to BR1 and BR2 protection classes are 100.24 MPa and 45.48 MPa, respectively. The projected values for BR3 and BR4 classes are 66.70 MPa and 68.93 MPa.

These values enable the calculation of any potential CLT thickness required to prevent (or allow) bullet penetration using the Poncelet formula. These apparent dynamic strengths are values that supplement the technical data in the literature for determining the ballistic performance of plywood material. The results obtained would predict the conditions in preparation for the next experiment or real conditions.

Optimisation of the Poncelet model parameters ($\alpha = 0.0968$ kg/m; $\beta = 3467$ kg×m/s^2) yields a predicted conditional extreme penetration depth of 140.1 mm, demonstrating high model reliability with an approximation error of 0.028 %.

Finite Element Method for the Numerical Modelling of CLT

The experiment was theoretically verified using ANSYS Workbench (ANSYS 2023 R2) and the Explicit Dynamics finite element solver, applied in a manner similar to LS-DYNA for modelling short-duration, high-velocity impact events. In the finite element method, the structure is discretised into finite elements with simple geometric shapes. The finite element model was numerically simulated to validate the obtained results. Such a simulation provides enhanced insight into material deformations, stress distribution, and the interaction between the projectile and the target material [35].

CLT panels were used to generate specimens. In building security studies, most ballistic research considers only normal-impact conditions, where the angle between the projectile velocity vector and the surface normal vector is zero since this configuration yields in the maximum projectile penetration depth. First, the materials used are defined. Lead was used for the 9 mm Parabellum projectile. CLT material was defined manually, as it is not included in the ANSYS material library. The adhesive layer was not modelled explicitly, as its effect is negligible relative to the overall CLT thickness and would significantly increase computational complexity. The geometric objects of the projectile and the CLT block are created in the ANSYS DesignModeler environment. The objects are modelled as solid bodies. The projectile is represented in a simplified geometry to ensure mesh element quality in subsequent stages, while maintaining dimensional consistency with a NATO 9 mm Parabellum projectile.

The numerical simulation employs a finite element mesh to ensure accurate process modelling. A hexahedral finite element mesh is used for the CLT plate, consisting of cube-shaped elements with dimensions of 2 mm × 2 mm × 2 mm. Accordingly, the entire CLT plate is discretised into small 2 mm cubes, with the total number of elements selected to achieve stable model convergence, representing a compromise between solver (Autodyn) computation time and solution quality. For the 9 mm projectile, a tetrahedral (triangular pyramid) finite element mesh is applied, which is more suitable for representing the projectile's ogive geometry. Due to the projectile shape, mesh quality was repeatedly refined to eliminate minimal elements that would significantly increase simulation time. The total number of elements exceeded 150,000, representing an optimal balance between computational efficiency and accuracy. The finite element meshes of the projectile and CLT plate in the Ansys environment are shown in Fig. 2.4.

Initially, the model is not subjected to pre-stresses or pre-deformations. Most Ansys analysis settings are left at their default values. The simulation time is manually specified as 0.0004 s, and the initial projectile velocity is set to 345 m/s. Fixed support boundary conditions are applied to all side surfaces of the CLT plate. Projectile spin is also introduced during flight, consistent with real firing conditions, as firearm barrels are rifled by default. This ensures stabilisation of the projectile and a straight flight trajectory.

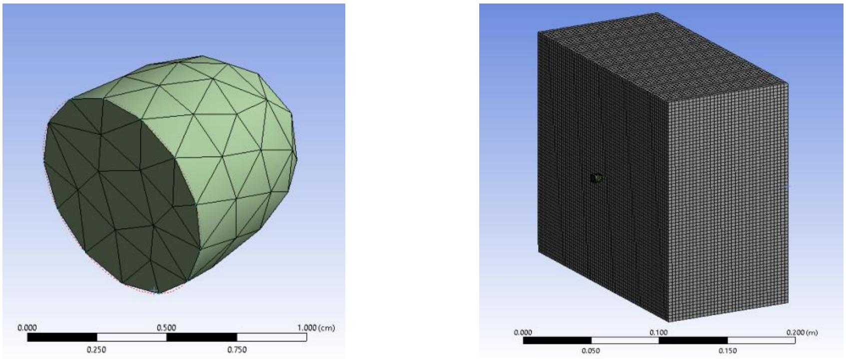


Fig. 2.4. Finite element mesh of the projectile and CLT plate in the ANSYS environment.

In the simulation results, the quantities of interest include elastic deformation of the material (equivalent elastic strain) and equivalent stress (equivalent von Mises stress). The interaction of a 9 mm projectile with CLT panels of C100 and C140 thickness was simulated. The obtained results are presented in Fig. 2.5.-2.7.

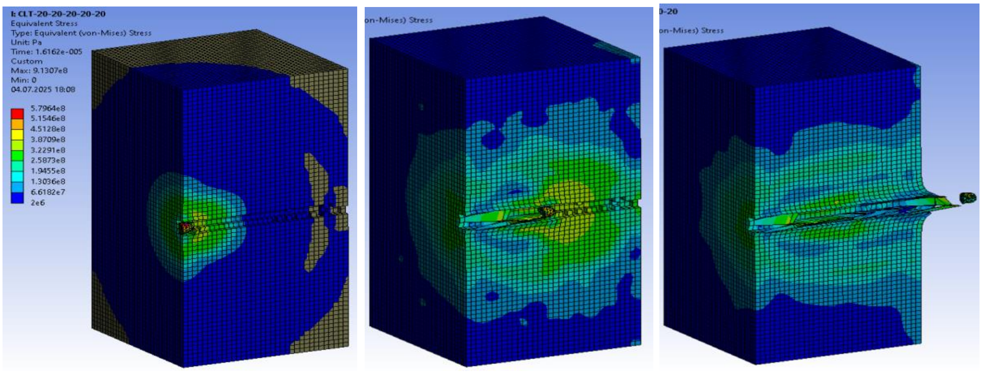


Fig. 2.5. Equivalent stress in the projectile and material for CLT 100 mm (20-20-20-20-20). The projectile penetrates and perforates the CLT material, leaving a distinct projectile path.

The simulation results provide insight into the load conditions experienced by the CLT material during projectile penetration. For the C100 the projectile perforates the material, consistent with the experimental observations. Although the projectile entry diameter is small, the impact generates a significant shock wave that affects a substantially larger volume of the material, several times the projectile's size. Material damage and distortion of the finite (mesh) elements along the projectile path are also pronounced. Upon exiting the material, the damage is directed toward the exit side, as observed experimentally.

In the case of the C140, the projectile also perforates the material. Despite the small entry diameter, the impact generates a shock wave that extends over a significant portion of the material, exceeding the projectile's size by several times. Based on the simulation results, the CLT material is damaged beyond the immediate entry zone, suggesting that a cluster of subsequent projectiles could potentially penetrate progressively deeper into the material.

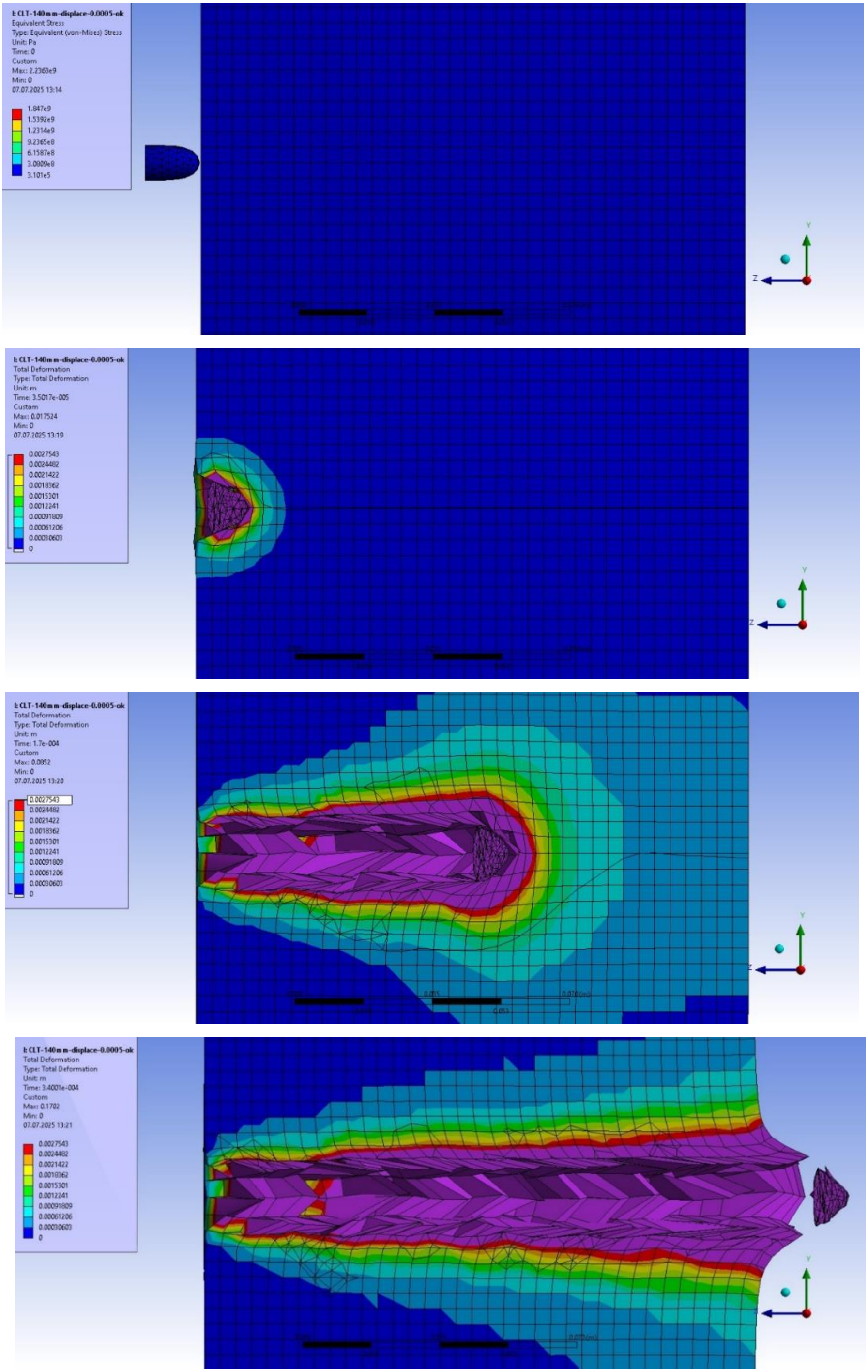


Fig. 2.6. Projectile penetration and perforation of CLT 140 mm (40-20-20-20-40).
Deformation of the projectile is observed.

The conclusion is that neither 100 mm nor 140 mm CLT panels can stop a 9 mm projectile fired from an 8 m distance. This finding is consistent with the experimental results. Such panels may be used in combination with other materials (e.g., special gypsum boards such as Torro, UHMWPE, or similar) for the enclosure walls of temporary or relocatable buildings where there is a risk of small-arms fire using this type of ammunition. It was concluded that the numerical model can predict the behaviour of CLT under projectile impact with sufficient accuracy (approximately 90 %).

Fig. 2.7 shows the bullet's behaviour in the C150 material. The bullet stops just before exiting at a depth of 146 mm, which matches the experimental data.

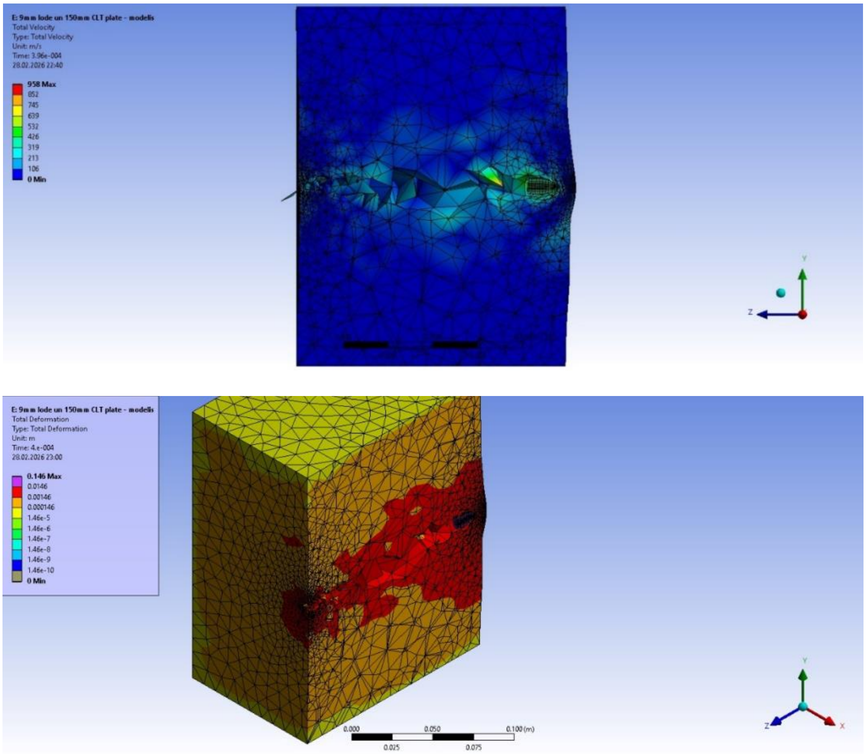


Fig. 2.7. Bullet penetration into the C150 material and its perforation. Material deformation is visible. In the C150 material, the bullet stops just before exiting.

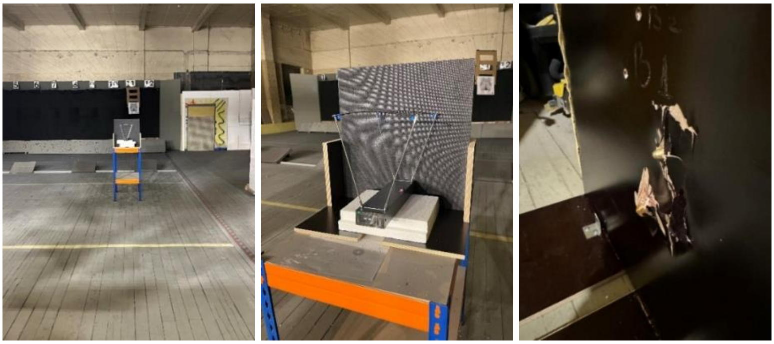
Sample modelling in Ansys Workbench software replicated the experimental results. Only a CLT wall with a minimum thickness of 150 mm can stop the projectile.

2.2.2. Experimental and Theoretical Investigation of Plywood

Experimental shooting tests were conducted at a shooting range on 27 mm thick laminated single-panel birch plywood LF-CPR/CE-DoP-01 manufactured by Riga® JSC Latvijas Finieris (19 veneer layers, formaldehyde adhesive), assembled into two- and three-panel configurations with simple joints. Although plywood testing was partly performed during preliminary experiments (see Section 2.2), the present study focuses on chronograph measurements. The objective was to determine the residual projectile velocity after exiting the target material or, in the case of projectile arrest, the stopping location and corresponding penetration depth when the plywood ballistic resistance exceeds the projectile kinetic energy. The measured plywood density was 770 kg/m³. Specimen dimensions were square (500 ± 5) mm × (500 ± 5) mm, in accordance with EN 1063. Test specimens were loosely mounted in a frame to avoid additional effects of ballistic impact (movement) on the target material. The environmental conditions in the testing facility were identical to those described in Section 2.4 (temperature: +10.4 °C, relative humidity: 72 %), as the tests were conducted consecutively.

Fig. 2.8 illustrates the experimental setup and procedure at the shooting range. In image (a), the firing distance to the target specimen (8.315 m) is shown, while image (b) presents the velocity measuring device (chronograph) used to determine the projectile velocity upon entering the material. Image (c) shows the plywood specimen after projectile impact, exhibiting projectile-induced deformation.

The observed deformations are relatively minor, with cracks primarily occurring in the laminated outer layers. Due to the cross-laminated structure, the plywood forms irregularly shaped splinters. Wood typically fractures along the grain direction, and splinter propagation is observed from the projectile exit point outward along the projectile path, most commonly forming an uneven fracture “cone” on the exit side, which is clearly visible.



a b c

Fig. 2.8. Experiment at the shooting range (a), velocity measuring device (chronograph) positioned before the specimen (b), and projectile arrest in the third plywood panel (c).

A single plywood panel reduced the projectile velocity by an average of 85.8 m/s, corresponding to less than 25 % of the initial projectile velocity of 345.1 m/s, or only about 5 % of the kinetic energy required to meet protection class BR2. As expected, the projectile fully penetrated the panel. Two assembled panels reduced the projectile velocity by an average of 204.4 m/s, corresponding to approximately 60 % of the impact velocity of 339.7 m/s before penetration, or about 24 % of the dissipated kinetic energy. This result was anticipated, as preliminary tests and calculations (Section 2.2) clearly indicated that two panels were unable to stop the projectile. When three panels were tested (3 × 27 mm = 81 mm plywood), the projectile was arrested in the third panel, as shown in Fig. 2.8 (c), resulting in a penetration depth of 79 mm, corresponding to 72 % of the required kinetic energy (projectile mass 8 g). Since the projectile’s initial velocity did not coincide with the maximum velocity specified for protection class BR2, empirical data (Fig. 2.10) were used to determine that a plywood thickness of 84.5 mm would reliably satisfy BR2 protection requirements. The relationship observed in Fig. 2.10. exhibits a polynomial trend.

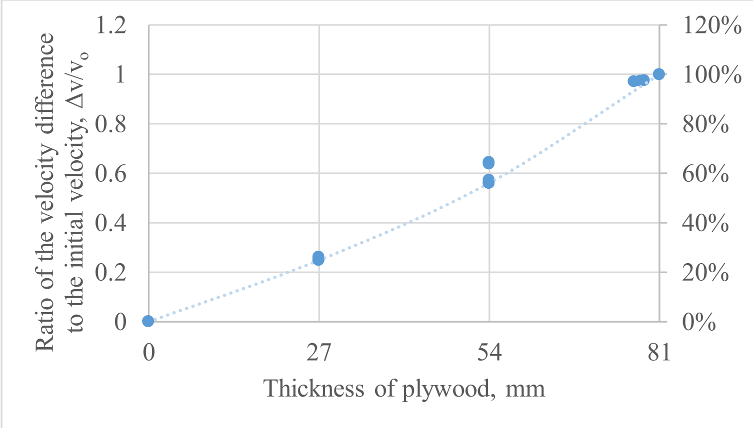


Fig. 2.9. Ratio of the absorbed velocity difference in plywood material to the initial bullet velocity as a function of material thickness.

Two combined panels reduced the bullet velocity by an average of 204.4 m/s, which is 57 % of the initial velocity of 339.7 m/s at impact before perforation, and 59 % of the required dissipated energy for the BR2 class. This result was expected, as the first test results and calculations (Section 2.1) clearly showed that two panels are insufficient to resist the bullet. The testing results are presented in Fig. 2.9.

When experimentally testing three panels, i.e., 3 × 27 mm = 81 mm plywood, the bullets became embedded in the third panel (see Fig. 2.8 (c), producing a penetration depth of 79 mm. This corresponds to 72% of the required kinetic energy (bullet mass 8 grams). Since the initial bullet velocity did not correspond to the maximum value defined for the BR2 protection class, empirical data (graph in Fig. 2.10) were used to determine that 84.5 mm thick plywood would reliably comply with the BR2 protection class. The graph shows a second-order polynomial relationship. The presence of the quadratic term indicates that as plywood thickness increases, the bullet velocity loss increases at an accelerating rate, meaning the material absorbs progressively more impact impulse.

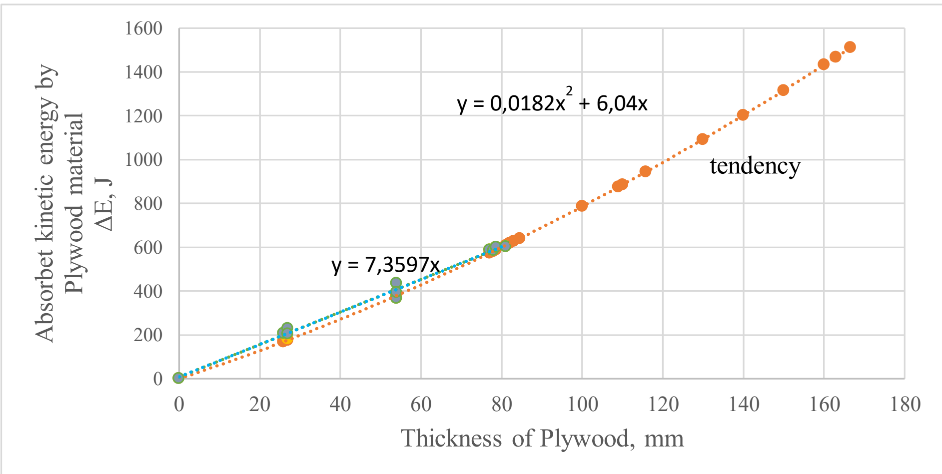


Fig. 2.10. Absorbed energy of plywood as a function of material thickness. Green markers indicate experimental results; the orange line represents the extrapolated trend.

Thus, the results are consistent with theoretical predictions, indicating that 81 mm thick plywood can stop a projectile with an impact velocity of 340.5 m/s. Considering that the maximum initial projectile velocity for protection class BR2 is 400 m/s and the projectile mass is 8.0 g, corresponding to a kinetic energy of 640 J, a plywood thickness of 87 mm is required to stop the projectile reliably. If plywood panels thinner than 87 mm are combined with additional layers – such as Kevlar sheets, UHMWPE, special gypsum boards, or air gaps between panels – the graph can be used to estimate the potential energy absorption capacity of these layers. The trend toward thicker plywood specimens can be inferred from the presented curves.

In a scientific study by Koene and Willemsen [61], the Poncelet formula was applied to plywood as the target material with a Janka hardness of 5.01 kN, a moisture content of 12,7 %, and a density of 682 kg/m^3. Using an internal material stress coefficient of α = (0.0167 ± 0.0040) kg/m and a material strength parameter of β=(5053 ± 200) kg × m/s^2, a penetration depth of P = (77.7 ± 23.4) mm was obtained. The absolute error was determined using indirect error propagation, resulting in a deviation of approximately 30 %. Consequently, the possible range of penetration depth P is (54.3–101.1 mm), representing an extensive interval. Therefore, a more precise determination of the model parameters is required to improve the accuracy of penetration depth predictions.

Based on the absorbed kinetic energy data for a given plywood thickness, the minimum required plywood thickness for each protection class according to EN 1063 was determined from the graph in Fig. 2.10 (see Table 2.7). The resulting minimum thicknesses for protection classes BR1 to BR4 were 26 mm, 85 mm, 122 mm, and 167 mm, respectively. For safety reasons, the calculated wall thicknesses corresponding to the penetration depths were rounded up to the nearest millimetre. The projectile initial velocities and masses were adopted in accordance with EN 1063; however, the initial velocity specified for protection class BR2 differs from the experimentally investigated maximum value of 345.1 m/s. The results indicate that projectile mass significantly influences penetration depth. For design safety, an additional safety criterion should be applied to the calculated penetration depths by increasing the number of plywood layers toward the thicker configuration.

Table 2.7

Characteristics of the Bullet and Plywood Material for Each Protection Class BR1-BR4

Protection class	Characteristics of the bullet						Characteristics of the material					
	E, J	m, g	v_0, m/s	C	d, mm	A, mm^2	ρ, kg/m^3	α, kg/m	P, mm	β, kg×m/s^2	R_t, MPa	ΔR_t, MPa
BR1	169	2.6	360	0.34	5.7	2.55×10^{-5}	770	0.0067	**26**	6082	**238.46**	**12.18**
BR2	640	8.0	400	0.342	9.0	6.36×10^{-5}	770	0.0167	**84.5**	6313	**99.29**	**5.01**
BR3	943	10.2	430	0.34	9.0	6.36×10^{-5}	770	0.0166	**122**	6284	**98.84**	**4.80**
BR4	1511	15.6	440	0.30	10.9	9.33×10^{-5}	770	0.0212	**167**	7167	**76.85**	**3.89**

Using Equation (1.3), the apparent dynamic strength R_t, MPa, of the material is determined, a parameter specific to each target material and its protection class. Accordingly, the empirically obtained apparent dynamic strength values for birch plywood corresponding to protection classes BR1, BR2, BR3, and BR4 are 238.46 MPa, 99.29 MPa, 98.84 MPa, and 76.85 MPa, respectively. These values enable the calculation of projectile penetration depth for plywood of any thickness using the Poncelet formula. Protection class BR1 represents a lower-threat condition (low-power handgun), which explains the markedly different apparent dynamic resistance compared with the higher protection classes.

These apparent dynamic strength values represent parameters that can be added to technical reference data for assessing the ballistic performance of plywood materials. The obtained data enable predictions for preparing for subsequent experiments or for real-world applications.

Using the formula in the UFC standard and assuming a birch plywood hardness of 2205 lbf (9.828 kN), the penetration depth for protection class BR2 was calculated to be 82.4 mm, which is slightly lower than the experimentally determined value of 84.5 mm. Although the prediction falls within 3 %, this formula is primarily intended for steel targets.

Optimising the Poncelet model parameters (α = 0.0153 kg/m; β = 5874 kg×m/s²) yields a predicted conditional extreme penetration depth of 80.5 mm, demonstrating high model reliability with an approximation error of 0.011 %. The optimisation of the Poncelet formulation reveals a conditional extremum.

The study results confirm that birch plywood is a conditionally predictable, modellable, and quantitatively characterizable ballistic material, whose bullet-resistant performance can be described mathematically and applied in the practical design of wall structures.

2.2. Summary

1. CLT and plywood can provide handgun ballistic protection up to 400 m/s, but increased thickness raises cost and weight, requiring a trade-off between protection level and practicality.
2. The Poncelet formula is a practical tool for estimating projectile penetration depth; however, its material-dependent parameters require refinement, particularly for layered materials such as CLT. By calibrating these parameters with experimental data, the minimum wall thickness for CLT and birch plywood can be predicted for projectile velocities and masses corresponding to protection classes BR1–BR4 (330–450 m/s, 2.5–15.7 g), thereby extending the existing ballistic material database.
3. Processing of experimental data. Experimental results showed the following.

For CLT panels:

- on average, CLT absorbs 1.61 m/s of projectile velocity per 1 mm of thickness.
- the minimum CLT thicknesses are for BR1 60 mm, for BR2 – 180 mm (176 mm), BR3 and for BR4 – 200 mm (185 mm and 199 mm).
- refined Poncelet model parameters were obtained experimentally. The apparent dynamic strength R_t of CLT was determined for BR1, BR2, BR3, and BR4 as 100.24 MPa, 45.48 MPa, 66.70 MPa, and 68.93 MPa, respectively. These values extend the technical literature and can be used for modelling the ballistic performance of timber materials.
- numerical modelling (Ansys Explicit Dynamics) using von Mises stress analysis showed projectile perforation of 100 mm and 140 mm CLT panels and stopped before 150 mm, consistent with experimental tests.

For plywood panels:

- the minimum plywood thickness for BR1 – 26 mm, for BR2 – 85 mm, for BR3 – 122 mm, and for BR4 – 167 mm;

- the apparent dynamic strength R_t of birch plywood was determined for BR1, BR2, BR3, and BR4 as 238.46 MPa, 99.29 MPa, 98.84 MPa, and 76.85 MPa, respectively.

4. Application of empirical data for determining protection classes. Based on EN 1063 classification, the minimum bullet-resistant thicknesses are summarised in Table 2.11.

Table 2.11

Comparison of Minimum Material Thicknesses Across Materials and Protection Classes

Protection class	Projectile's mass (EN 1063) m, g	Initial velocity v_o, m/s	Min thickness of CLT, mm	Min thickness of Plywood, mm	Difference in thickness, %
BR1	2.6	360	60	26	57
BR2	8.0	400	176 (~180)	85	52
BR3	10.2	430	185 (~ 200)	122	34
BR4	15.6	440	199 (~ 200)	167	16

Birch plywood shows higher ballistic efficiency than CLT (54 % for BR1–BR2 and 40 % for BR1–BR4); the decreasing difference indicates the future studies for BR3–BR4 classes.

5. Determination of rational parameters (optimisation) for protection class BR2.

For CLT material, the conditional optimal penetration depth is P=140.1 mm with parameters:

$\alpha = 0.0968$ kg/m, $\beta = 3467$ kg×m/s².

For plywood material, the conditional optimal penetration depth is P=80.5 mm with parameters:

$\alpha = 0.0167$ kg/m, $\beta = 5874$ kg×m/s².

3. METHODOLOGY FOR BALLISTIC RESISTANCE EVALUATION

To ensure the validity of the research and compliance with measurement standards, a research methodology is developed that must be followed cyclically throughout the study. In the general methodology of ballistic experiments, the key stages include developing the research concept based on an analysis of the theoretical literature, selecting experimental data samples, analysing, and verifying results, and adapting the data to other protection classes for validation.

The methodology summary is based on the reviewed scientific literature, with consideration given to the works of K. Sanborn, L. Koene, and M. T. Lo Ricco. The methodological framework employs a qualitative approach and is structured into five steps that outline the research procedure, defining the minimum required wall thickness for CLT and birch plywood walls for the protection classes BR1 and BR2, in accordance with EN 1063.

The general methodology for the experimental work is divided into five stages:

Stage 1. Theoretical part, which consists of a literature review on existing bullet-resistant wall systems, scientific findings, comparative analyses, and adaptation of relevant theoretical models.

Stage 2. Experimental part, which includes selection of the target material (wood species, density, thickness, fibre orientation, moisture content, hardness, type of thermal treatment, number of layers in glued materials, layer thickness, and adhesive type); preparation of specimens in accordance with standardised dimensions; selection of weapons and ammunition depending on the experimental objective; definition of test conditions (shooting setup layout, test stand arrangement and supports, need for a bullet-catching wall, number of shots); and technical instrumentation. This instrumentation includes projectile velocity measurements using a chronograph (velocimeter) to determine initial and residual velocities before and after the specimen, as well as high-speed cameras to document projectile–target interaction, deformation, and fragmentation. Measurement of penetration depth, projectile deformation (number and size of fragments, number of impacts), channel diameter, and splinter formation is performed using radiographic and visual methods. Additional optional equipment includes laser scanning, acoustic impulse sensors, and related measurement systems, as well as safety provisions (certified shooting range, safety briefings for personnel and experimental participants, legally approved ammunition, and shooting permits). Testing conditions are fully or partially defined by ballistic standards such as EN 1063, EN 1522 / DIN EN 1522, EN 1523 / DIN EN 1523, BS 5051, UL 752, ASTM F1233-08, NIJ Standard-0108.01, and the UFC 4-023-07 document.

Stage 3. Experimental data analysis, which includes evaluation of velocity, energy, and specific energy per 1 mm of target thickness, reflecting the test results. The experimental data are compared with theoretical values, graphs are constructed, and dependent parameters are determined empirically. Mean values, confidence intervals, standard deviations, confidence limits, and regression equations are established.

Stage 4. Results validation, in which the obtained data are verified against applicable standards and theoretical models, and deviations from regulatory requirements are identified.

Stage 5. Results approval (applicability), which involves the development of proposals for supplementing regulatory documents in the field of ballistics.

The schematic diagram of the methodological algorithm is shown in Fig. 3.1.

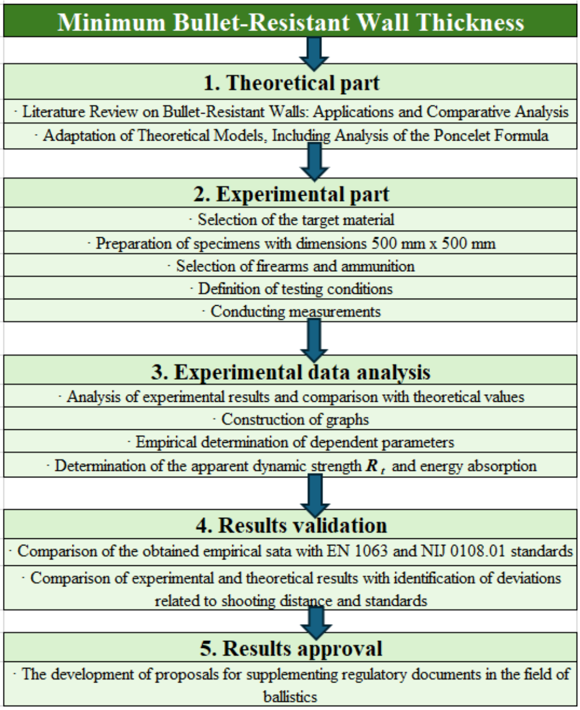


Fig. 3.1. General algorithm of the methodology.

A more detailed methodological framework specific to the field of ballistics is presented below, outlining the practical application of ballistic experiments for determining penetration depth and relevant parameters, along with the existing limitations and assumptions. The methodology is based on analysis of the mechanical properties of materials, differences in impact kinetic energy, and empirical relationships between wood density, projectile parameters, and impact-induced penetration depth.

To verify the methodology's accuracy, experimental results were compared with the EN 1063 standard's threshold values for protection classes BR1 and BR2, and trends were extrapolated for classes BR3 and BR4. The developed methodology enables predicting the required wooden wall thickness without conducting the whole experimental process, thereby reducing financial costs and risks, and accelerating the design of bullet-resistant buildings. This study demonstrates an integrated experimental, analytical, and numerical approach to investigating the ballistic resistance of CLT and plywood panels, linking real experimental data with theoretical and numerical models.

In the practical part of the methodology, calculations are performed using experimentally determined material parameters. A near-BR2 protection class is selected as the experimental classification basis, from which results are extended to other protection classes by accounting for differences in impact kinetic energy, determined by standardised projectile mass and maximum initial velocity values.

A graphical representation of the methodology is shown in Fig. 3.2.

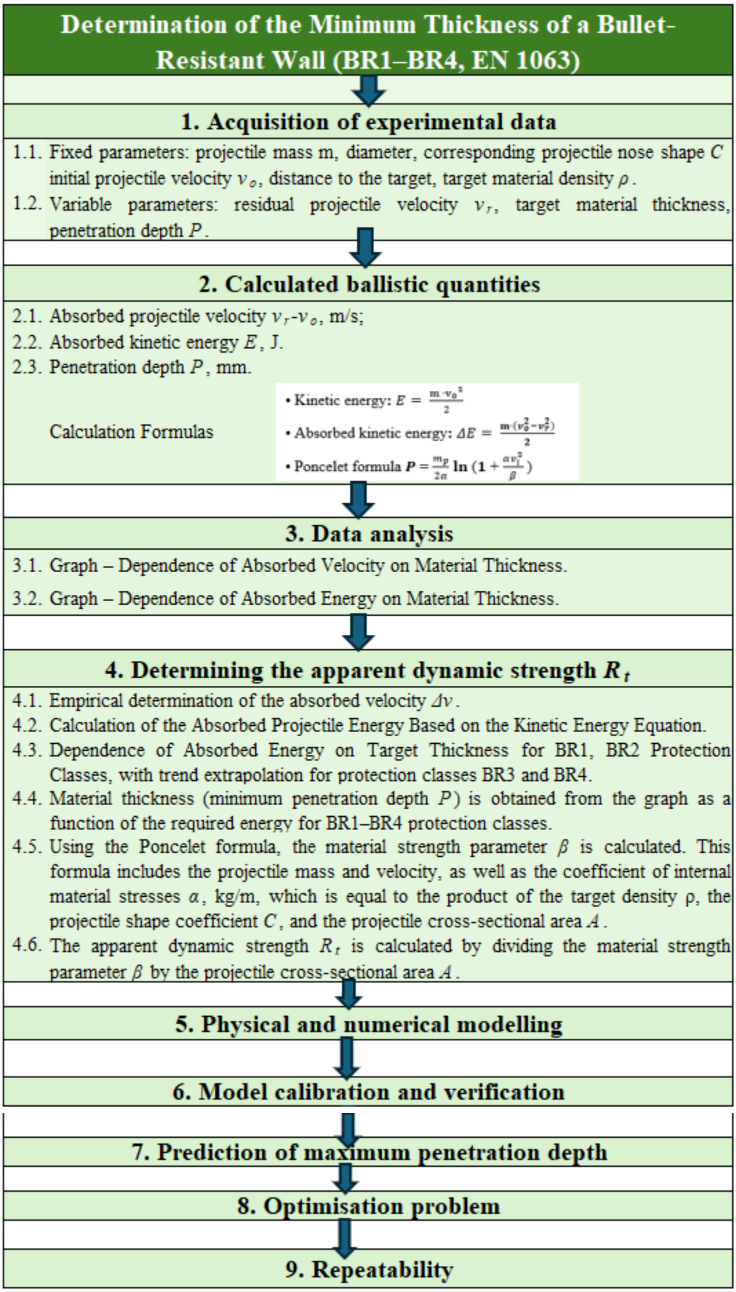


Fig. 3.2. Methodology flow diagram.

The calculated results were compared with experimental data to validate the methodology's accuracy. The comparison demonstrates that the proposed methodology allows prediction of the required thickness of glued wooden walls with sufficient reliability for protection classes BR1 and BR2 and indicates a trend for BR3 and BR4 classes in accordance with the EN 1063 standard.

The methodology integrates experimentally obtained data with theoretical modelling, using the Poncelet formula, absorbed energy, and the finite element method.

The following methodological stages are listed and described in detail: acquisition of experimental data; calculation of ballistic parameters; data analysis; determination of the apparent dynamic strength R_t; physical and/or numerical modelling; model calibration and verification; prediction; optimisation; and repeatability.

1. Acquisition of experimental data

1.1. First, the constant parameters and measurements are defined, which in the ballistic case include projectile mass m, projectile diameter, corresponding projectile nose shape *C*, initial projectile velocity v_o, distance to the target, and target material density ρ.

1.2. Variable parameters include target material thickness, residual projectile velocity v_r, and projectile penetration depth *P*.

1.3. All quantities are expressed in the International System of Units (SI): kg, m, s, J

1.4. Each projectile impact is marked on the target specimen and documented photographically.

1.5. Projectile velocity is measured before and after impact with the target material.

2. Calculated ballistic quantities

2.1. Absorbed projectile velocity, Δv, m/s, is obtained as the difference between the initial velocity and the residual velocity.

2.2. Absorbed kinetic energy, ΔE, J, is obtained as one half of the product of the projectile mass and the difference between the squares of the initial and residual velocities.

2.3. Penetration depth, *P*, mm, is measured using a rigid wire and a hand ruler.;

2.4. Physical Modelling and Fundamental Calculation Formulas:

• kinetic energy: $E = \frac{m \times v_o^2}{2}$;

• absorbed kinetic energy: $\Delta E = \frac{m \times (v_o^2 - v_r^2)}{2}$;

• Poncelet formula $\boldsymbol{P} = \frac{m_p}{2\alpha} \ln \left(1 + \frac{\alpha v_i^2}{\beta}\right)$.

3. Data analysis

3.1. Tables and graphs were created to present the obtained data.

3.2. Observations, trends, and projections regarding influencing factors are described.

4. Method for determining the apparent dynamic strength R_t

4.1. The absorbed projectile velocity of the target is determined experimentally $\Delta v = v_r - v_o$.

4.2. The absorbed squared projectile velocity is determined experimentally $v_r^2 - v_o^2$.

4.3. The absorbed projectile energy is calculated using the fundamental kinetic energy equation.

4.4. A graph is constructed showing the dependence of absorbed energy on target thickness for protection classes BR1 and BR2, with trend extrapolation for protection classes BR3 and BR4.

4.5. From the graph, the thickness of each material – corresponding to the minimum penetration depth $P -$ is determined as a function of the required energy for protection classes BR1–BR4.

4.6. Using the Poncelet formula (Eq. (1.2)), the material strength parameter β is calculated. This formula includes the projectile mass and velocity, as well as the coefficient of internal material stresses α, kg/m, which equals the product of the target density ρ, the projectile shape coefficient *C*, and the projectile cross-sectional area *A*.

4.7. The apparent dynamic strength R_t is calculated by dividing the material strength parameter β by the projectile cross-sectional area *A*, in accordance with Equation (1.3).

5. **Physical and numerical modelling.** The physical (numerical) model is developed using the finite element method with ANSYS Workbench (ANSYS 2023 R2) and the Explicit Dynamics solver module, in a manner similar to LS-DYNA for modelling short-duration, high-velocity impact events.
6. **Model calibration and verification**
   Experimental penetration depth results are compared with theoretically determined values.
7. **Prediction of maximum penetration depth**
   A predictive analysis is performed to determine the maximum penetration depth.
8. **Solution of the optimisation problem**
   The optimisation procedure allows the determination of the optimal penetration depth and modelling of extreme boundary conditions, thereby enhancing the methodological robustness and practical applicability of the study.
9. **Repeatability.** The number of repetitions is 3–5 shots.
   Safety Considerations. Shooting operations and safety supervision at the shooting range are conducted by qualified personnel. Prior to firing, inspection of the firearm barrel and ammunition is performed to ensure compliance with safety standards. Only the shooter is present in the firing zone, and the projectile flight path area is isolated. Observers use hearing protection devices.

Unlike other international studies, the proposed methodology is enhanced in that it:

- provides experimentally validated, practically applicable data and results for the design of ballistic wall structures made of CLT and plywood.
- demonstrates validation of theoretical and numerical models against empirical results.

Accordingly, the scientific relevance of the study is reflected in the practical applicability, methodological integrity, and combined experimental–numerical accuracy of the proposed approach, which together enable prediction and optimisation of the response of glued timber protective structures under different protection levels.

The developed methodology allows the prediction of the ballistic performance of glued timber panels and can be applied in the design of protective structures.

4. PRACTICAL CASE STUDY: DESIGN OF BALLISTIC WALL THICKNESS

This chapter presents a practical example, including input data and a solution for the application of a timber-based ballistic wall.

Input data:

In the Italian city of Varna, a police station is being designed using CLT timber materials. The client specifies that certain internal walls of the station should be ballistically protected, for example, walls of short-term holding rooms. An Austrian responsible engineer proposes a wall configuration consisting of a 140 mm CLT panel combined with a 27 mm plywood panel. The questions are: Will such a wall provide sufficient ballistic resistance? Furthermore, does the layer sequence (i.e., the orientation of the wall assembly) affect the ballistic resistance of this combined system?

Additional data:

It is known that police firearms are .44 Remington Magnum calibre, i.e., protection class BR4 according to EN 1063. This means that, unlike the experimental part of the doctoral study focused on BR2 (projectile mass 8 g and initial velocity 340 m/s), the current design case involves a projectile mass of 15.6 g and an initial velocity of 440 m/s. A comparison of projectile mass and initial velocity between the classes is provided in Table 4.1. Accordingly, the wall must now protect against a projectile that is almost twice as heavy and has an initial velocity 99 m/s higher, resulting in an approximately 870 J increase, i.e., a 2.36-fold higher initial kinetic energy. Although integrating thermal insulation materials into wall assemblies may increase the overall ballistic resistance of the system, this effect is secondary for typical in-service layer thicknesses. A detailed investigation of this factor would require a separate experimental approach, which is beyond the scope of the present study.

Table 4.1

Comparison of Bullet Mass and Initial Velocity Between Classes

	Projectile's mass m, g	Initial velocity v_o, m/s	Initial kinetic energy E, J
BR2	8	400 ± 10	640
BR4	15.6	440 ± 10	1510
Difference	7.6	99	870
Scale	1.95	1.29	2.36

Question: Do the obtained data enable the calculation of the minimum required thickness of CLT and plywood walls to withstand accidental or intentional projectile impact?

Problem solutio

1) *First solution – a combination of a 140 mm CLT panel and a 27 mm plywood panel.*

Based on the obtained experimental data, a 27 mm thick plywood panel absorbs 204 J of the projectile's kinetic energy. In comparison, a 140 mm thick CLT panel reliably absorbs 370 J. Consequently, the combined system of 27 mm plywood + 140 mm CLT absorbs a total of 574 J. This indicates that the selected solution would resist only 38 % of the required kinetic energy, as shown in Table 4.2.

Table 4.2

Tabulated Evaluation of the First Solution

Material	Thickness, mm	Stored energy according to empirical data ΔE, J	Percentage of the required 1511 J stored energy
CLT	140	370	24.5 %
Plywood	27	204	13.5 %
Total	167	574	38 %

2) Second solution. What is the optimal combination of CLT and plywood?

Based on the Poncelet formula and the empirically determined results of this study, it was found that a combination of 180 mm CLT and three plywood panels (81 mm) absorbs 1374 J of kinetic energy, which is still insufficient. This result is presented in Table 4.3.

Table 4.3

Tabulated Evaluation of the Second Solution

Material	Thickness, mm	Stored energy according to empirical data ΔE, J	Percentage of the required 1511 J stored energy
CLT	180	770	50.1 %
Plywood	81 (3 × 27)	604	40.0 %
Total	261	1374	90.1 %
CLT	200	1511	100 %
Plywood	167 (~6 × 28)	1511	100 %

Based on the calculations, it is concluded that it is more effective to use either a 200 mm thick CLT wall or a 167 mm thick plywood wall, without combining the two materials, to withstand the most powerful firearms corresponding to protection class BR4.

3) Third solution: use a 180 mm thick CLT panel and reinforce it with Knauf Torro or Knauf Diamant gypsum boards

In this configuration, the 180 mm CLT panel alone would protect only 770 J, corresponding to 50.1 % of the total required energy. Therefore, additional ballistic panels are clearly required to ensure both the physical safety and psychological comfort of building occupants. Information on Knauf Torro and Knauf Diamant boards is provided in the author's study [36], where a 28 mm Torro gypsum board alone was shown to stop a 9 mm projectile and absorb an initial velocity of 338 m/s.

Furthermore, the manufacturer of Knauf Torro has tested the board using a .44 Remington Magnum projectile (velocity 430–450 m/s), confirming compliance with the BR4 performance level specified in EN 1063.

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5. BALISTIC PERFORMANCE OF MULTILAYER WALL SYSTEMS

The previously developed methodology enables a quantitative assessment and the formulation of well-founded conclusions regarding the ballistic resistance characteristics of multilayer structures. The methodology is based on determining the energy absorption of individual layers and applying the principle of energy balance. Composite protection solutions are proposed, such as multilayer wall systems including CLT–Kevlar–thermal insulation and plywood–UHMWPE, which could potentially improve the ballistic resistance of modular building structures while reducing overall building weight. The analysis shows that the application of the methodology is more accurate for walls consisting of two different layers rather than three or more. In the case of two materials, the energy difference method more precisely determines the ballistic parameters of the specimen, as mutual interaction effects and cumulative errors are reduced. Combined CLT and plywood wall structures were experimentally tested, and finally, eight ballistic wall configurations were theoretically compared according to three aspects: cost, thermal transmittance, and weight.

5.1. Experimental and Theoretical Investigation of CLT Walls with Insulation

In the study, CLT wall configurations were tested, in which a 140 mm thick CLT layer absorbs approximately 58% of the energy required for the BR2 protection class. By optimising material use and thus reducing wall weight, it is expected that additional layers may provide the remaining ballistic resistance.

One wall configuration (samples A, A2, B, B2) included aramid fabric (Kevlar) layers applied on different sides of the CLT panel, while a reference wall without aramid reinforcement was used for comparison (samples C, C2). The wall assembly consisted of a 12.5 mm standard gypsum board, a 200 mm mineral wool insulation layer, a C140 mm CLT panel (40-20-20-20-40 mm layup), and a 12.5 mm fire-resistant gypsum board, as required by fire safety regulations. The wall structure was based on a commercially available system from CLT Profi Ltd (Latvia), which typically incorporates an 80 mm thick CLT panel; however, for ballistic purposes, this was experimentally replaced with a 140 mm thick panel. The adhesive used in the CLT panels was urea-formaldehyde. In standard construction practice, the wall panel is additionally equipped with a vapour barrier membrane and finishing layers; however, as their ballistic resistance is negligible, they were omitted from the experiment. Although the timber battens supporting the finishing layers may locally contribute to ballistic resistance, they do not cover the entire panel surface and may not be intersected by a projectile; therefore, no additional timber elements were included. As ballistic reinforcement, two layers of woven aramid (Kevlar) were applied in two configurations: between the CLT panel and the fire-resistant gypsum board (sample A), and between the thermal insulation layer and the CLT panel (sample B). Firing tests were conducted from both sides of the CLT wall to assess whether and to what extent the CLT layer could stop the projectile.

The thermal transmittance of the tested wall assemblies was calculated theoretically, resulting in U = 0.154 W/(m^2×K). Based on theoretical calculations, the mineral wool thickness could be reduced to 150 mm while still complying with the requirements of LBN 002-19 for the maximum allowable thermal transmittance of residential building walls.

The wall layer composition for wall A (with Kevlar fabric placed between the CLT panel and the fire-resistant gypsum board), including layer thicknesses, measured material densities (based on weighed specimens), and corresponding theoretical densities, is presented in Table 5.1 and Fig. 5.1. The CLT material is assumed to correspond to C24-grade solid timber as per the manufacturer's data. The experimental conditions are consistent with those described in Chapter 2. Table 5.1 shows that the measured densities generally correspond well with the theoretical values, except for CLT.

Table 5.1

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	Mineral wool Knauf Insulation Ecoboard	200	13.9	13.8
3	CLT, CLT Profi	140	461.7	420 (Wood C24)
4	Kevlar fabric × 2	2x0.9	217.8	222.2
5	Gypsum plasterboard Knauf red GKF	12.5	829.8	800

Fig. 5.1. CLT wall (sample A) – schematic representation of the layers (see Table 5.1) 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.)

Ordinary gypsum plasterboard exhibits low ballistic resistance [36]. Moreover, is used in CLT wall assemblies primarily as a fire-protection layer, as required by fire safety regulations in several European countries for timber buildings. The Kevlar fabric used in the experiments was knitted (two-thread knit) rather than woven, with the selection based on market availability. Knitted Kevlar fabrics are commonly applied as supplementary protection in abrasive environments, for example, in protective sports clothing used in motorsports.

The results showed that, when firing toward sample A ((Fig. 5.2 (a)) from the exterior side (starting from the grey gypsum board), the projectiles penetrated the CLT material to a maximum depth of 127 mm. The governing penetration parameter is not the average of five shots but the maximum penetration depth, as this represents the most critical and hazardous condition for civilian users of the building or wall. The Kevlar fabric did not entirely stop the projectiles as intended; instead, the bullets perforated the fabric and became embedded in the

CLT. The maximum penetration depth in the composite wall system was 339.5 mm (12.5 mm + 200 mm + 127 mm).

(a) (b) (c)

Fig. 5.2. CLT wall specimens after the experiment (a–c)

Four projectiles were fired at wall sample B. Two were stopped by the wall, while the other two were not. For the two penetrating projectiles, the maximum residual velocity was 57.1 m/s; therefore, it was determined that the wall reduced the projectile velocity by 289.3 m/s, calculated from the maximum measured impact velocity of 345.8 m/s before entering the specimen. For the non-penetrating projectiles, the maximum penetration depth within the wall was 343.3 mm (12.5 mm + 200 mm + 1.8 mm + 129 mm). The projectiles became embedded in the CLT material at a maximum depth of 129 mm, without reaching the Kevlar fabric layer. No experimental data are available for the opposite wall-firing direction (sample B2).

By comparing samples A and B, it can be concluded that the Kevlar fabric provides additional resistance, as the penetration depth in sample A was smaller than in sample B, and sample A stopped all four projectiles. This effect is likely related to the fact that the projectile must overcome an additional interface to continue its motion.

However, the experimental test also showed that firing a projectile through only two layers of 0.9 mm Kevlar fabric reduced its velocity by only 5 m/s ((see Fig. 5.2 (b)). Only later, through a review of theoretical studies, was it identified that a small number of Kevlar fabric layers is ineffective at stopping projectiles and may instead allow them to penetrate deeper into the target material (in the referenced study – ballistic gel). A noticeable reduction in projectile velocity and penetration depth was observed only when the number of Kevlar layers was increased significantly (to 12 layers) [37].

For the reference wall C without Kevlar reinforcement, the projectile penetrated the wall from both firing directions. The maximum residual velocity after exiting the wall was 43.5 m/s, indicating that the wall reduced the projectile velocity by 296.3 m/s. This reduction is comparable to that observed in walls incorporating Kevlar fabric; therefore, it can be concluded that the knitted Kevlar fabric has a limited effect on ballistic resistance, primarily due to its structural characteristics.

In future research, ballistic experiments should be conducted using woven (rather than knitted) Kevlar fabric, as woven fibre structures are theoretically more effective in absorbing and redistributing projectile kinetic energy along the fibre length. When firing from the opposite side of the wall, where the fire-resistant gypsum board forms the front layer, the results differ.

For asymmetric layered wall systems, the direction of impact relative to the material sequence is a critical factor influencing ballistic performance.

Table 5.2

Analysis of the Shooting Results for CLT Walls

Direction of the shooting	Sample	No.	Parameters			Absorbed energy	CLT absorbs	wool+gyps+K
			E_o J	E_r J	$\Delta v/v_o$, m/s	ΔE J	ΔE J	ΔE J
wool-CLT	Kevlar between insulation and CLT	**A**	478	0	1.00	478	344	134
CLT-wool	opposite direction	**A2**	478	0	1.00	478	173	305
wool-CLT	Kevlar between CLT and fireproof gypsum	**B_1a**	476	0	1.00	476	350	118
		B_1b	467	12,9	1.00	454		69
CLT-wool	opposite direction	**B2**	-	-	-	-		
wool-CLT	Reference wall without Kevlar	**C_1a**	461	12,81	0.83	448		79
wool-CLT		**C_1b**	462	3,672	0.91	458		81
CLT-wool	opposite direction	**C2**	462	2	0.94	460		97

Table 5.2 presents the analysis of the results, based on the previously obtained experimental finding that 140 mm CLT (C140) absorbs 380 joules of kinetic energy. To determine the contribution of the remaining layers to energy dissipation, the energy absorbed by the CLT layer was subtracted from the total absorbed energy of the wall specimen.

Using the previously obtained graph (Fig. 2.9), the absorbed energy was determined. In specimens A, A2, and B, the bullet was stopped; therefore, the varying penetration depth in the CLT material must be analysed. However, since in some of these specimens the bullet fully perforated the wall, those values are excluded from the analysis.

In specimens B, C_1a, C1b, and C2, the bullet did not perforate the wall. The calculations show that the mineral wool + gypsum board + Kevlar layers together absorb 69–81 J of energy, which represents a relatively small energy range. From the author's previous study, "Ordinary gypsum plasterboard and Knauf Torro gypsum plasterboard bullet-proofing," it is known that a single gypsum board absorbs only a small amount of kinetic energy, and that the effect of two layers of Kevlar is not statistically significant. This leads to an estimation of the ballistic resistance contribution of the 200 mm mineral wool layer.

When calculating the absorbed kinetic energy for specimens B, C, and C2, it is evident that the total does not reach the threshold of 640 J corresponding to the BR2 class level.

The results showed that a 140 mm CLT composite wall with 200 mm mineral wool insulation and a Kevlar layer placed between the insulation layers is sufficient to stop a bullet fired at up to 341.6 m/s. However, it does not provide BR2-level protection, as the absorbed kinetic energy does not reach the required 640 J for BR2. The bullet-stopping capability varied depending on the shooting direction and the layer sequence. The CLT layer is the main energy absorber, as the bullets were embedded directly in the CLT material. Calculations indicate that mineral wool + gypsum board + Kevlar together absorb 69–81 J of kinetic energy. Fire-protection (gypsum board) and thermal insulation layers cannot be considered significant ballistic shielding components. For a multilayer CLT wall to achieve the BR2 protection level, the composition must be improved, including increased CLT thickness (>140 mm) and a more effective fibre layer (woven Kevlar ≥12 layers or UHMWPE). The previously developed methodology enables quantitative assessment and formulation of conclusions regarding the ballistic resistance characteristics of multilayer structures.

5.2. Experimental and Theoretical Investigation of UHMWPE-plywood

In this study, plywood research was extended by investigating composite plywood–UHMWPE wall systems to adapt the calculation methodology for determining or predicting the ballistic resistance of additional materials. Both load-bearing and non-load-bearing building wall panels were developed using UHMWPE sheets in various configurations combined with birch plywood. During ballistic experiments, it was observed that the panels' ballistic response is strongly influenced by the arrangement of materials within the panels. Separate UHMWPE panels of different thicknesses were also tested to monitor material damage. The study analysed possible damage mechanisms and the ballistic resistance of panels depending on the façade-side material. These load-bearing and non-load-bearing building panels are intended for use either individually or as part of combined protective systems against small-calibre projectiles or blast fragments, protecting both intentional and accidental gunfire.

The specific birch plywood thickness and grade were selected because they are relatively widely used, as well as sufficiently thick and possessing high strength and hardness (density 670 kg/m^3) to enable prediction of stopping a 9 mm calibre bullet. The material functions as a projectile-entangling "mesh" within the composite structure, as the bullet deforms upon impact, causing significant energy losses by dispersing its energy over a larger area and thereby reducing its ability to continue motion. The coefficients of thermal expansion of the two materials are not similar: for UHMWPE (density 930 kg/m^3) it is $\alpha = 2\times10^{-6}$ K [38], whereas for plywood (at 20 °C and 65% relative humidity) α = 28–31×10-6 K.

The experiment was conducted under controlled conditions at a shooting range in Riga. During the experiment, the air temperature ranged from +5.1–7.0 °C (in January), and the relative humidity was 65–70 %. The shots were fired by a semi-professional shooter, thereby bringing the situation closer to real-life conditions.

A limitation of the study was the use of UHMWPE material in only one layer, as UHMWPE is not the most economically advantageous material. A future objective is to use recycled UHMWPE material, thereby reducing panel costs and increasing sustainability. Initially, individual UHMWPE panels and laminated plywood material were tested separately to assess the ballistic damage in each material.

The specimens were tested at an impact velocity of 345 m/s using a theoretically non-deformable bullet with a steel jacket, fired from a distance of 10 m from the target. The diameter of the flying bullet was 9 mm, and its mass was 8 grams. [116] Based on the performed calculations, the impact energy, i.e., the kinetic energy, was calculated and used to assess the damage caused by the projectile. If the projectile passes through the target with residual energy close to zero, the material is considered to have reached its ballistic limit. [8], [39], [40]

Using the basic kinetic energy formula, the energy imparted by the bullet is determined. This panel absorbs 476 J of energy, which is 74% of the energy of the BR2 protection class.

$$E_{kin} = \frac{0.008\text{kg} \times (345\text{m/s})^2}{2} = 476.1 \text{ J}.$$

Individually, the materials did not stop the bullet; therefore, in the second stage of the experiment, it was necessary to verify whether the combination of these two materials would provide greater ballistic resistance. Load-bearing and non-load-bearing wall panels were thus developed using UHMWPE in various combinations with birch plywood. These combinations are also presented in Table 5.3.

Table 5.3

Ballistic Resistance of Plywood–Polyethylene Panels

Panel No.	Position	Material	Projectile	Did bullets perforate?	Panel in which the bullet stopped	Measured penetration depth, mm
1_1	front	20 mm UHMWPE	9 mm Luger FJM	yes	–	>53
	rear	32 mm plywood				
1_2	front	32 mm plywood		no	UHMWPE	53 ± 1
	rear	20 mm UHMWPE				
2_1	front	20 mm UHMWPE		no	plywood, 2nd layer	61 ± 1
	rear	2x32 mm plywood				
2_2	front	2x32 mm plywood		no	UHMWPE	74 ± 1
	rear	20 mm UHMWPE				

Panel No. 1_1. The bullet perforated both materials. As a result, in the adhesive layer of the plywood, 11 cross-laminated birch veneer sheets delaminated; in the third layer from the panel edge, damage to the wood veneer layer was observed. Two control shots were performed, and in both cases the bullets were not stopped.

Fig. 5.3. Sample 1_2. Plywood–UHMWPE. [116]

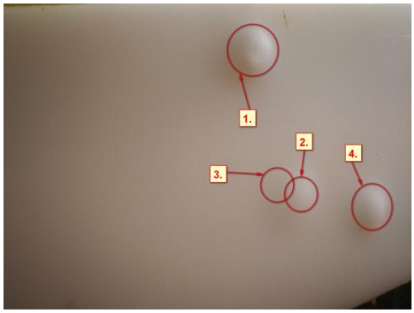

Fig. 5.4. Sample 1_2. Plywood–UHMWPE, PE bulging. [116]

Four shots were fired from a handgun at Panel No. 1_2. The panel stopped the bullet with the first shot (see Fig. 5.3). The bullet perforated the plywood, but the UHMWPE layer stopped it. Local deformations were observed in the polyethylene, corresponding to the bullet trajectory. After pressing out the PE panel (see Fig. 5.4), a thickening of the material was detected at the centre point, possibly caused by rapid internal temperature fluctuations. Since the melting temperature of UHMWPE is 130 °C, a short-term impact at such a temperature does not cause permanent deformation. [116] The maximum experimentally measured penetration depth was 53 mm. Figure 5.5 schematically illustrates the cross-sectional representation of the panels.

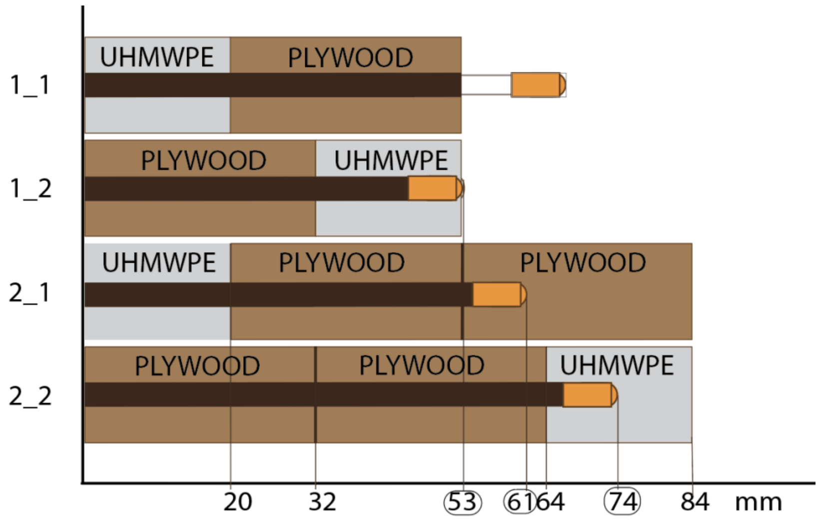

Fig. 5.5. Experimental projectile penetration depth (mm) for each panel configuration.

By analysing the obtained penetration depths and using previously acquired experimental ballistic data for plywood material, the bullet resistance of the UHMWPE material was calculated. A graph (Fig. 5.6) was obtained, along with a second-order polynomial relationship showing the material's ability to resist a bullet as a function of UHMWPE panel thickness.

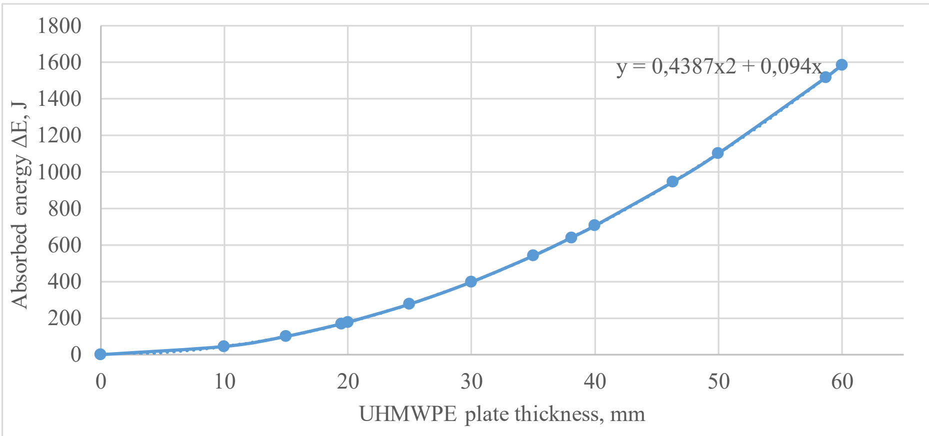

Fig. 5.6. Amount of absorbed energy as a function of UHMWPE plate thickness.

From the graph, it can be read that to achieve BR1 and BR2 protection classes, the required UHMWPE thickness is 19.5 mm (rounded to 20 mm) and 38.1 mm (rounded to 40 mm), respectively.

Using the developed methodology, the apparent dynamic strength Rt can also be determined for UHMWPE material. The calculation results are presented in Table 5.4. These apparent dynamic strength values would supplement existing technical literature data for evaluating the ballistic performance of plywood materials. The obtained data can be used to predict conditions when preparing for another experiment or for real-life applications.

Table 5.4

Characteristics of the Bullet and Plywood Material for Each Protection Class BR1-BR4

Protection class	Characteristics of the bullet						Characteristics of the material					
	E, J	m, g	v_0, m/s	C	d, mm	A, mm^2	ρ, kg/m^3	α, kg/m	P, mm	β, kg×m/s^2	R_t, MPa	ΔR_t, MPa
BR1	168	2.6	360	0.34	5.7	2.46E-05	930	0.0081	**20**	29	**1.15**	0.01
BR2	640	8.0	400	0.342	9.0	6.36E-05	930	0.0177	**40**	537	**8.44**	0.08
BR3	943	10.2	430	0.34	9.0	6.36E-05	930	0.0177	**46**	1059	**16.65**	0.17
BR4	1510	15.6	440	0.30	10.9	9.33E-05	930	0.0260	**59**	3127	**33.53**	0.34

Polyethylene and plywood panels arranged in the correct sequence withstood frontal impacts from a light handgun projectile using 9 mm Luger ammunition fired from a Glock 17. The most effective configuration in terms of bullet resistance was 1 × 32 mm plywood combined with 20 mm UHMWPE. The bullets were stopped in the polyethylene layer. The hardness of UHMWPE, combined with plywood, provides impact resistance to bullets with an initial velocity of up to 345 m/s. These panels can function as bullet-resistant wall elements.

UHMW polyethylene begins to soften after absorbing the bullet's initial energy. The melting process indicates that the kinetic energy is sufficient to heat the polyethylene to approximately 130 °C.

After impact, it is possible to visually restore the panel using various methods, such as applying elevated temperature to fuse the UHMWPE material. Alternatively, the damaged area can be reinforced or replaced with a stronger material (for example, a metal rod). This can be done immediately to prevent open channels for subsequent shots.

The next experiment would involve varying the thickness of plywood and UHMWPE panels (particularly reducing plywood thickness in tests 2_1 and 2_2) to ensure that the minimum possible thickness is used while achieving maximum wall lightness. Further research could also include combinations with other ballistic materials, such as aramid fibre boards [9].

In panels composed of multiple materials with different physical properties, the position (sequence) of each material within the composite structure is critical. The order of materials can significantly influence the panel's ability to withstand ballistic loads. Laminated plywood and UHMWPE specimens tested separately did not achieve the BR2 ballistic limit; however, configurations with plywood on the outside (at least 32 mm) and UHMWPE on the inside (20 mm) performed better than the reverse sequence. These panels could be used as part of walls in various shelters, such as army headquarters and safe rooms, due to their relatively low density.

The minimum UHMWPE thickness required to stop the maximum initial kinetic energy specified in EN 1063 protection classes is: BR1 – 20 mm, BR2 – 38 mm; projected values are BR3 – 46 mm, BR4 – 59 mm. The Poncelet formula parameters were refined based on experimental results. Using the author's introduced method, the empirically determined apparent dynamic strength Rt of UHMWPE corresponding to BR1, BR2, BR3, and BR4 classes is 1.15 MPa, and 8.44 MPa; projected values are 16.65 MPa and 33.53 MPa. These values supplement existing technical literature and can be used in modelling the ballistic performance of UHMWPE material. However, these results should be experimentally verified to confirm whether this method is applicable beyond wood-based bonded elements.

5.3. Comparison of Ballistic Walls

In the study, eight selected, well-known, and commonly used wall structures (shown in Fig. 5.7) that have been tested to meet the BR2 class and are considered ballistically equivalent are theoretically compared. These structures consist of one or several material layers. This comparison aims to analyse bullet-resistant wall systems and identify the best (most advantageous) and worst (least advantageous) solutions within individual categories, as well as the overall best average solution, based on three additional aspects: cost, thermal transmittance, and weight. This review would assist construction companies, defence institutions, and managers of public buildings in selecting suitable ballistic materials for high-risk building walls. It also demonstrates that traditional materials do not only offer advantages but may also have significant drawbacks.

Fig. 5.7. Eight analysed ballistic wall systems, illustrated with representative images. [9], [20], [36], [41], [42], [43]

Building occupants are fully ballistically protected against intentional or accidental gunfire if the material absorbs the projectile and prevents it from penetrating the wall. These walls are generally bullet-resistant from both the exterior and interior sides, regardless of where the attack occurs. Ballistic protection largely depends on the shooting angle and distance [5]. However, this study does not include variables such as the influence of impact angle and shooting distance (in standard laboratory experiments, the distance to the target is 5 m). The study also defines experimental boundaries and does not address installation details, cost of assembly, variability of joints, ballistic resistance of connections, sudden changes in bullet velocity (e.g., accidental obstacles in the projectile path), bullet dimensions, bullet tip shape, ricochet probability, or fragment dispersion. The thicknesses of these eight wall materials provide the minimum ballistic resistance required to stop a 9 mm Glock 17 bullet, as identified in theoretical literature by other researchers or in the author's previous studies. According to EN 1063 for ballistic-resistant protective materials, their class would be BR2 [36], meaning resistance to bullet velocities up to 400 m/s. The material thickness may need to increase if a more powerful weapon is considered. The study evaluates four criteria (wall thickness, cost, thermal transmittance, and mass per square meter) based on the material's ballistic capability. The categories are rated using a point system from 1 to 8. In the cost evaluation, a score of "1" represents the least expensive wall solution and "8" the most expensive. For thermal transmittance, a score of "1" represents the best thermal performance (lowest heat loss), and "8" represents the poorest thermal performance. In the mass evaluation, a score of "1" represents the lightest wall and "8" the heaviest. Material cost was calculated for an 80 m² wall enclosing a 50 m² modular building (wall height 2.7 m) [5], [10], [13]. Installation costs were not included. Thermal transmittance was determined by the ratio of thermal conductivity (lambda value) to wall thickness. The internal and external surface thermal resistance values were not considered. Wall mass was calculated based on the density and thickness of each layer. Figure 5.8 presents the research results using a multi-criteria evaluation tool in the form of a radar chart, which graphically illustrates the comparative outcomes.

In the radar diagram, the material covering the largest area represents the overall most advantageous solution. The most economically advantageous (least expensive) solution is the 120 mm clay brick wall, whereas the most expensive wall is the 140 mm CLT wall with thermal insulation and an aramid layer, due to its technological production complexity – although it demonstrates superior thermal performance. The greatest heat loss occurs in the 6 mm steel plate without added insulation. The lightest ballistic walls are the 28 mm Torro gypsum boards, while the heaviest is the 120 mm clay brick wall due to its high density and thickness.

Overall, the most valuable and recommended solution is the 85 mm plywood wall combined with a 28 mm Knauf Torro board. Although plywood did not achieve the best rating in any single category, it maintained an optimal balance across all categories. The least recommended solution in this evaluation is the traditional concrete wall, due to its high mass and relatively low thermal performance; however, this drawback can be mitigated by adding thermal insulation. All eight walls can be used as ballistic panels in timber-frame modular buildings, which are not necessarily intended for long-term use.

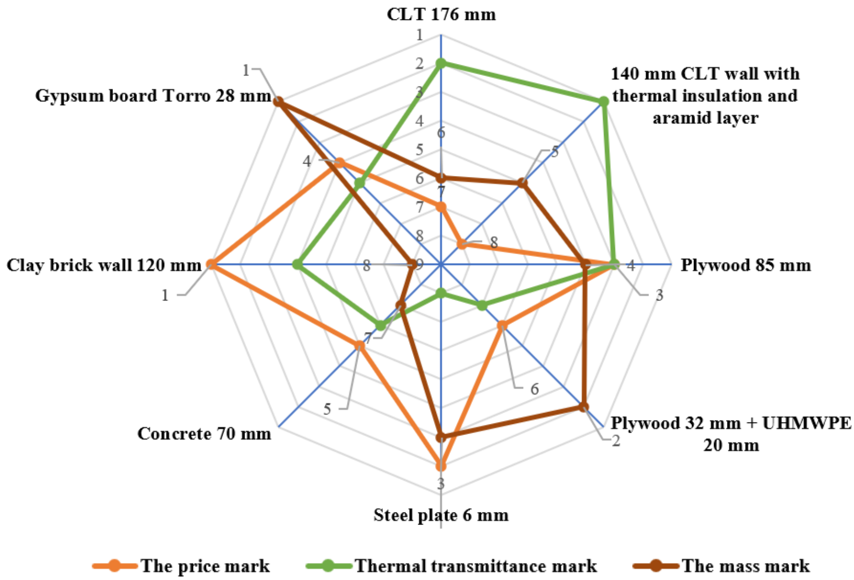

Fig. 5.8. Radar chart illustrating the suitable material depending on the intended application; 1 represents the best performance and 8 the worst.

CONCLUSIONS

The aim and objectives of the Doctoral Thesis have been achieved. The study presents a calculation methodology for the ballistic resistance design of bullet-resistant wall structures in modular buildings.

As a result of the doctoral research, the following conclusions were drawn:

1. The need for a new methodology is also demonstrated by the lack of experimental and theoretical comparison. Previous scientific studies have used the Poncelet and Euler–Robin formulas as theoretical models; however, validation against experimental results is still missing. Not all formula parameters have been disclosed, such as the apparent dynamic strength, which would enable more accurate determination of bullet penetration depth.
2. In the initial ballistic tests, theoretical penetration depth calculations using the Poncelet formula showed agreement with the experimental data. Accordingly, the selection of the test specimen/wall thickness was confirmed based on the theoretical calculations.
3. A calculation methodology for predicting the ballistic resistance of modular building wall structures for protection classes BR1 and BR2 in accordance with EN 1063 has been developed. The methodology is based on the analysis of material mechanical properties, impact energy balance, and empirical relationships between wood density, projectile parameters, and penetration depth. The methodology consists of the following stages: experimental data acquisition; calculation of ballistic parameters; data analysis; determination of apparent dynamic strength R_t, physical (numerical) modelling; model calibration and validation; prediction; optimisation; and repeatability assessment.
4. Using the method proposed by the author, the apparent dynamic strength of CLT and birch plywood was determined for protection classes BR1 and BR2. This enables the calculation of the maximum projectile penetration depth (or minimum wall thickness) for projectiles with a mass up to 8.0 g and velocities up to 400 m/s, and allows extrapolation trends for BR3 and BR4 classes with projectile masses up to 15.6 g and velocities up to 440 m/s.
5. For the development of the calculation methodology, the obtained experimental data were analysed in comparison with the limit values specified in EN 1063 for protection classes BR1 and BR2, as well as projected trends for BR3 and BR4. The results show that:
   - the ballistic resistance of glued timber is non-linear and can be modelled using the Poncelet formula, polynomial relationships, and empirically determined parameters.
   - for protection classes BR1 and BR2, birch plywood demonstrates approximately 54 % higher ballistic efficiency than CLT; for BR1–BR4 classes, the difference is approximately 40 %.

   For CLT panels:

   - experimental results indicate that the minimum CLT thickness in accordance with EN 1063 is 60 mm for BR1, 176 mm for BR2, with extrapolated values of 185 mm for BR3 and 199 mm for BR4;
   - refined Poncelet model parameters were obtained. Using the author's method, the apparent dynamic strength Rt of CLT was determined to be 100.24 MPa (BR1), 45.48 MPa (BR2), 66.70 MPa (BR3), and 68.93 MPa (BR4), providing new data to the technical literature;

- numerical modelling (ANSYS Explicit Dynamics) using von Mises stress analysis confirmed projectile penetration through 100 mm and 140 mm CLT panels, in agreement with experimental observations.

For plywood panels:

- the minimum plywood thickness required to stop the maximum kinetic energy specified by EN 1063 is 26 mm (BR1), 85 mm (BR2), 122 mm (BR3), and 167 mm (BR4);
- the apparent dynamic strength;
- *Rt* of birch plywood was determined as 238.46 MPa (BR1), 99.29 MPa (BR2), 98.84 MPa (BR3), and 76.85 MPa (BR4), providing quantitative parameters for ballistic performance modelling.

Transitioning from BR2 to BR4 protection classes requires either a 200 mm thick CLT wall or 167 mm of plywood, with no material combination. A combined wall of 180 mm CLT and 81 mm plywood fails to meet the required energy absorption of 1511 J; therefore, such a combination is not justified.

6. The developed methodology enables the prediction of the required timber wall thickness without full-scale experimental testing, thereby reducing financial costs, safety risks, and design time for bullet-resistant buildings.
7. Parameter optimisation enables the determination of optimal penetration depths and extreme boundary conditions, enhancing methodological robustness and practical applicability. The optimised Poncelet model yields predicted penetration depths of 140.1 mm for CLT (α = 0.0968 kg/m; β = 3467 kg×m/s^2) and 80.5 mm for plywood (α = 0.0153 kg/m; β = 5874 kg×m/s^2), in agreement with experimental data.
8. More effective ballistic protection can be achieved by integrating timber with supplementary materials (e.g., Kevlar, mineral wool, UHMWPE). In multilayer panels composed of materials with different physical properties, the material sequence significantly affects ballistic performance.
9. The Poncelet formula parameters were refined based on experimental results. Using the method introduced by the author, the apparent dynamic strength Rt of UHMWPE was empirically determined for BR1, BR2, BR3, and BR4 classes as 1.15 MPa, and 8.44 MPa, with projected values of 16.65 MPa and 33.53 MPa. The minimum UHMWPE thickness required to stop the maximum initial kinetic energy specified in EN 1063 protection classes is: BR1 – 20 mm, BR2 – 38 mm, with projected values BR3 – 46 mm and BR4 – 59 mm. These values supplement technical literature data and can be used in modeling the ballistic performance of UHMWPE material. However, these results should be experimentally verified to confirm whether this method is applicable beyond wood-based bonded elements.
10. The previously developed methodology enables quantitative evaluation and the formulation of well-founded conclusions regarding the ballistic resistance characteristics of multilayer structures. The methodology is based on determining the energy absorption contribution of individual layers and applying the principle of energy balance. In addition, composite protection solutions are proposed, such as multilayer CLT–Kevlar–insulation and plywood–UHMWPE wall systems, which could potentially improve the ballistic resistance of modular building structures. The analysis shows that the methodology is more reliable and less uncertain for walls consisting of two different layers rather than systems

with three or more layers. In the case of two materials, the energy difference method more accurately determines the ballistic parameters of the specimen, as mutual interaction effects and cumulative errors are reduced.

11. In panels composed of multiple materials with different physical properties, the position (sequence) of each material within the composite panel structure is critical. The order of materials can significantly influence the panel's ability to withstand ballistic loads. When comparing the most promising ballistic wall solutions, the study showed that the most cost-effective option is the 28 mm Torro wall. From a thermal transmittance perspective, CLT walls with 200 mm mineral wool insulation perform the best, while the worst performance is observed in a steel plate without thermal insulation. In terms of weight, the lightest ballistic wall solution is the 28 mm Knauf Torro board, whereas clay brick and concrete walls are the heaviest. Overall, the most advantageous solutions are the 85 mm plywood wall and the 28 mm Knauf Torro board. These materials are recommended for timber-frame structures as temporary building solutions in cases of accidental or intentional gunfire. The least favourable overall solution proved to be the traditional concrete wall.
12. Recommendations for practical implementation and standardisation.
    - incorporate apparent dynamic strength values Rt into Poncelet-based calculations: 100.24 MPa and 45.48 MPa for CLT, and 238.46 MPa and 99.29 MPa for plywood for BR1 and BR2 classes;
    - adopt minimum material thickness requirements: CLT – BR1 60 mm, BR2 176 mm; plywood – BR1 26 mm, BR2 85 mm.

RECOMMENDATIONS FOR FURTHER RESEARCH

To promote the development of the field of ballistics in protective wall applications and to initiate similar studies, the following preparations for experiments are recommended:

- test specimens using a ballistic testing rig (mechanical firing device), thereby eliminating shooter-related errors and unintended movements, and ensuring higher accuracy and repeatability of results;
- test CLT panels of identical thickness but with different layer configurations and to analyse in greater detail the influence of layering, layer thickness, number of layers, and adhesive type on ballistic performance.

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