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Analysis of the Characteristics of External Walls of Wooden Prefab Cross Laminated Timber

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Abstract: A balanced combination of heat flows creates suitable conditions for thermal comfort—a factor contributing to the quality of the internal environment of buildings. The presented analysis of selected thermal-technical parameters is up-to-date and suitable for verifying the parameters of building constructions. The research also applied a methodology for examining the acoustic parameters of structural parts of buildings in laboratory conditions. In this research, selected variant solutions of perimeter walls based on prefab cross laminated timber were investigated in terms of acoustic and thermal-technical properties. The variants structures were investigated in laboratory but also in model conditions. The results of the analyses show significant differences between the theoretical or declared parameters and the values measured in laboratory conditions. The deviations of experimental measurements from the calculated or declared parameters were not as significant for variant B as they were for variant A. These findings show that for these analyzed sandwich structures based on wood, it is not always possible to reliably declare calculated values of thermal-technical and acoustic parameters. It is necessary to thoroughly examine such design variants, which would contribute to the knowledge in this field of research of construction systems based on wood.

Keywords: acoustic; cross laminated timber; CLT; prefab construction; thermal; wood; wood construction

1. Introduction

The use of wood in all areas of life is almost as old as humanity itself. Wood, being one of the oldest construction materials, is by no means obsolete for use in construction. In recent decades, wood as a construction material has become increasingly popular among architects, designers and potential investors [1,2]. The great potential of this construction material is the result of development in manufacturing and of the construction of wood-based buildings [3,4]. Whether independently or in combination with concrete, glass or steel, wood can be adapted to all types of construction projects, such as new constructions or reconstructions, residential or non-residential, low-rise or high-rise buildings [5–7].

A quality spatial concept of a wooden building can be understood as an interaction between defined requirements in the design phase [8,9], specification of materials and implementation of the building in accordance with the design solution [10–12]. The requirements of wood-based constructions in design and implementation are closely related to the properties of wood and wood-based materials [13].

Wooden houses and wooden constructions have accompanied us since time immemorial. Wood has excellent physical, technological, aesthetic and utility properties. In terms of the positive properties of wood, wooden houses are very popular and allow the building of an economically and environmentally friendly and modern building with long life and durability [14–16]. However, when choosing materials for wooden buildings, it is necessary to take into account their thermal insulation properties in the context of the subsequent operation of buildings and their energy efficiency [17–20]. The choice of materials and technologies is not easy and, in addition to the technical parameters that determine the suitability of their use in a particular type of construction, the financial aspect and, to a large extent, the ecological thinking of the investor play a role [21–24]. Structural systems of wooden buildings are very diverse in today's houses, not only in terms of construction and insulation materials used, but also in terms of the technological equipment of the house, such as heat pumps, controlled ventilation or photovoltaics. Wooden buildings generally have low acoustic comfort during use, so it is necessary to focus on the acoustic spectrum when designing and implementing wooden buildings, so it is necessary to design the composition of structures and select materials to eliminate these disadvantages. Its choice depends on the chosen construction system [25–27]. In addition to classic materials, such as panels with mineral insulation clad with large-format boards (OSB, DHF, plasterboard and gypsum fiber boards), ecological materials come to the fore, such as hemp and straw insulation, sheep fleece, wood fiber insulation or blown paper-based insulation and wood. An alternative to sandwich constructions are massive constructions created from cross-glued cross laminated timber (CLT) formats, as they are made of wood and are increasingly used for the construction of modern wooden buildings. In addition to the standard requirements, wood-based houses should also meet the requirements for healthy living—i.e., contain as few materials containing pollutants as possible. Little attention is paid to the acoustic solution of the building, which is a mistake. The individual compositions of the structure should insulate the noise well, and at the floor level also dampen the impact noise [28–31].

The development of architecture and increased attention focused on the issue of technical assurance of the quality of the indoor environment required the formulation of acoustic requirements focused on the indoor environment with the users of persons [32–34]. An important finding is the effects of excessive noise on humans, which differ according to the activity performed by a person at a given time and from individual characteristics, i.e. from mental and physical mood [35–37]. From the point of view of noise protection, the insulating properties of the building structure in particular are important for the structure [38].

In addition to fire resistance, one of the sensitive places of wood-based buildings is sound insulation. It is well known that conventional wooden structures without appropriate modifications have worse sound-insulating properties than solid silicate-based structures [39]. Wood and wood-based materials are in some respects considered to have excellent acoustic properties (absorption, density, speed of sound propagation, etc.) [40]. From the point of view of the use of wood in building constructions, not all acoustic properties of wood are positive and desirable. Therefore, a deeper examination of the use of wood in building structures is needed. With the correct use of these properties in the overall composition of the structure, with the knowledge of the principle of sound propagation and construction principles, their acoustic properties, comparable to some silicate structures, can be significantly improved by effective measures [41]. Multi-layer walls of wooden buildings can, under certain circumstances, achieve the required acoustic parameters better than traditional masonry structures. In addition, unlike masonry structures, it is possible to influence these properties much more. While in masonry it depends practically only on the thickness and weight of the structure, in wooden construction it is the type of individual layers, their mutual arrangement and attachment, their distance, the distance of load-bearing parts of the structure and the size and filling of cavities between them [42]. This task is currently being pursued by several research and development institutions or manufacturers of building materials and structures in the European Union and around the world.

This research was a response to the need to verify the actual values of selected thermal-technical and acoustic parameters of construction solutions based on wood by confronting them with the calculated or declared values stated by manufacturers and providers of construction systems based on prefab cross laminated timber panels. In this research, various variant solutions of perimeter walls based on prefab cross laminated timber were investigated in terms of selected properties.

2. Materials and Methods

2.1. Description of Investigated Structures

Both of the examined design variants had the same supporting external wall system from prefab cross laminated timber panels.

CLT (cross laminated timber) is a construction product made of solid wood, made by transverse gluing at least three layers of single-layer laminated boards [43,44]. CLT panels are standardly produced in dimensions up to a width of approximately 3 m and a length of 16 m, and in thicknesses from 60 to 400 mm. Environmentally friendly, formaldehyde-free adhesives are used in the production (for example, various types of natural or synthetic resins, etc.). The panels are suitable for the construction of both interior and exterior walls, as well as for the construction of ceilings and roofs. The wide range of dimensions is compact and according to the requirements of the statics, it is possible to choose the appropriate size and thickness of the panels without the use of other supporting structures. The surface layer is produced in the appropriate quality by sorting the material directly during production [45,46]. In the case of requirements of the visible surface, it is not necessary to additionally install a visible plywood, joint or bioplate. When finished, according to the project, processed panels are transported to the construction site, where a professional company will build a rough construction of the house in a few days.

The essence of the compared constructions was the same load-bearing element made of prefabricated CLT panels. The first variant of the perimeter wall was insulated with EPS-based insulation (Table 1). The second variant used thermal insulation based on wood fiber as a more environmentally friendly alternative compared to the EPS thermal insulation (Table 2). The size of the investigated structures (2.5 × 2 m) was adapted to the climate chamber where the simulations were performed. Basic descriptive statistical methods and the non-parametric statistical Student t-test were used to analyze data [47]. The Student t-test was used to compare the examined data from the measurements of the variants in laboratory conditions. Statistical analyses were performed using STATISTICA 12 software.

Table 1. Material composition–variant A.

Layer Name	Volumetric Weight ρ (kg.m^3)	Layer Thickness d (mm)	Thermal Resistance R_d (m^2.K/W)	Thermal Conductivity Coefficient λ_d (W/(.m.K))	Diffusion Resistance Factor μ (-)
CLT	470	100	0.909	0.11	40–70
Material for gluing insulation panels	15–25	-	-	0.035	28
Thermal insulation—EPS	13.5–18	200	5.25	0.038	20–40
Construction glue	1400	2.5	-	0.45	25
Plastering	1200	2.5	-	0.5	25
Additional anchoring material					

Notes: CLT—Cross laminated timber.

Table 2. Material composition–variant B.

Layer Name	Volumetric Weight ρ (kg.m^3)	Layer Thickness d (mm)	Thermal Resistance R_d (m^2.K/W)	Thermal Conductivity Coefficient λ_d (W/(.m.K))	Diffusion Resistance Factor μ (-)
CLT	470	100	0.909	0.11	40–70
Material for gluing insulation panels	15–25	-	-	0.035	28
Thermal insulation—wood fiber	230	200	4.34	0.046	5
Construction adhesive	1400	2.5	-	0.45	25
Plastering	1200	2.5	-	0.5	25
Additional anchoring material					

Notes: CLT—Cross laminated timber.

2.2. Methods of Assessment of Selected Thermal-Technical Parameters

The investigated constructions were compared by means of the U value where this value was determined on the basis of data obtained from laboratory measurements and Formula (1) according to the standard STN 73 0540 [48].

$$U = \frac{q}{\theta_{ai} - \theta_{ae}} \left[\mathrm{W/m^2K}\right] \quad (1)$$

Notes: q-heat flow density (W/m^2); $\theta_{ai} - \theta_{ae}$—temperature difference between inner and outer surface (°C).

The ALMEMO5690-2 recording set (Ahlborn) was used to obtain data from laboratory measurements, with appropriate sensors for temperature, temperature flow, humidity and air flow. Laboratory measurements were simulated in a climate chamber (Figures 1–5). The climate chamber shown in Figure 1 is visualized using SketchUp 2019 software. The boundary conditions of the simulations were chosen according to EN ISO 10456 [49].

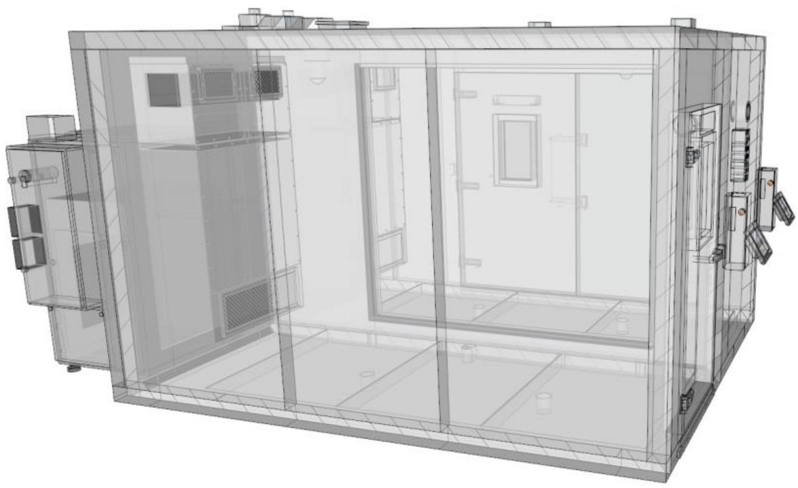

Figure 1. Climate chamber THERMOTRON.

Figure 2. Prefab cross laminated timber structure.

Figure 3. Locations of sensors on the interior side of the structure.

Figure 4. Measured variant A sample on the exterior side of the structure.

Figure 5. Measured variant B sample on the exterior side of the structure.

To compare the data obtained by measurements in laboratory conditions, the structures were also subjected to a computational model based on STN 73 0540 [48]. The computational boundary conditions were chosen to be comparable with laboratory simulations to maintain the validity of the comparison. Formula (2) was used in the computational models.

$$U = \frac{1}{R_i + R + R_e} \left[W/m^2K \right] \quad (2)$$

Notes: R_i—thermal resistance of the inside (m^2K/W); R_e—thermal resistance of the outside (m^2K/W); R—thermal resistance of construction (m^2K/W).

2.3. Methods of Measuring and Evaluating Acoustic Parameters

Measurement of sound reduction index (examined variants) was realized according international standard ISO 16283-1 [50]. For measurement, a low frequency method that is suitable for rooms with volume less than 25 m^3 was used.

A dodecahedron loudspeaker Norsonic Nor276 with power amplifier Norsonic Nor280 that generates white noise (Figure 6) was used as a noise source. Sound analyzer class 1 Norsonic Nor140 was used for measurement. NorBuild software was used for calculation.

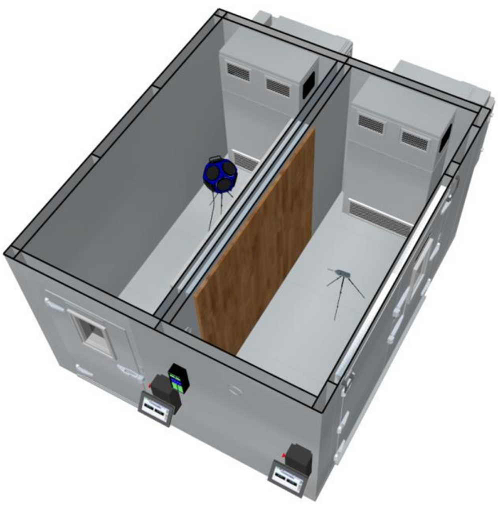

Figure 6. Location of measuring instruments for examining acoustic parameters in the climate chamber.

Measurement consists of measurement of sound pressure level in source room and receiving room during the active loudspeaker. Measurements were realized with two positions of loudspeaker. Sound pressure level was measured in room corners in source and receiving rooms in four positions 0.3–0.4 m from the corners. Background noise level was also measured in the receiving room. Reverberation time in the receiving room was also measured and calculated according to ISO 3382-2 [51].

For the comparison of measurements that were performed in laboratory conditions, the so-called declared or calculated values were also determined. The calculated values were determined on the basis of [52,53]. Such a comparison was desirable in order to verify and compare the measured values with the so-called declared ones. For these purposes, in accordance with the used standards and procedures, the boundary conditions of laboratory measurements and computational models were unified to ensure validity.

3. Results and Discussion

3.1. Analysis of Selected Thermal-Technical Parameters of the Examined Design Variants

Boundary laboratory conditions were simulated for 12 h and the individual values are shown in Figures 7 and 8.

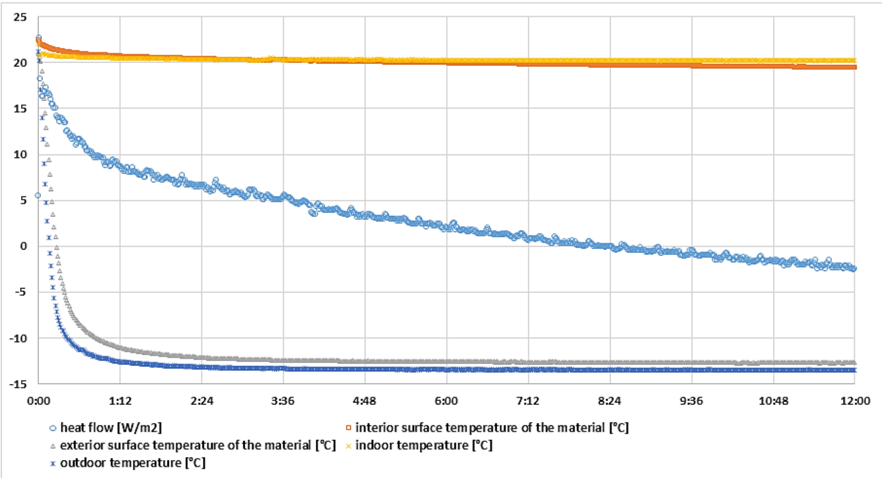

Figure 7. Data from laboratory measurements for variant A—EPS.

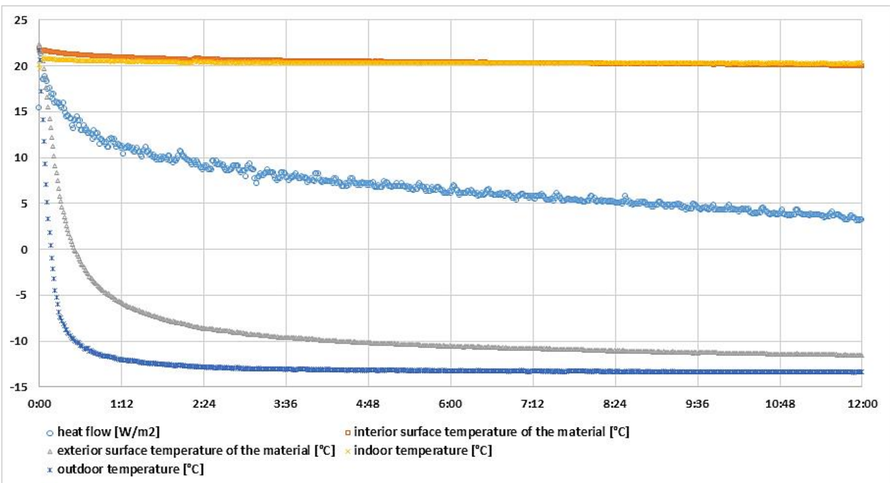

Figure 8. Data from laboratory measurements for variant B—wood fiber.

The following U values were found in the laboratory environment: variant A 0.064 ± 0.009 W/m^{2}K, variant B 0.114 ± 0.009 W/m^{2}K (Table 3). The difference between the constructions was 43.86% and was statistically significant ($p < 0.0001$).

Table 3. Steady state data U values.

	***U* Value (W/m^{2}K)**	***U* Value (W/m^{2}K)**
	Variant A	**Variant B**
Average	0.064	0.114
± std	0.009	0.009
Min	0.046	0.098
Max	0.081	0.137
Median	0.062	0.114
25th perc	0.056	0.108
75th perc	0.068	0.117
***t*-test ***	$p < 0.0001$ ***	

Note: ***—p value summary, *—steady state temperature of samples.

Laboratory measurements were also compared by means of computational models where the following U values were found: variant A 0.16 W/(m^2.K), variant B U 0.18 W/(m^2.K). The boundary conditions of the calculation were as follows: variant A θ_{si} = 19.33 °C, diffusion resistance 21.25 × 10^9 m/s, R = 6.043 m^2.K/W; variant B θ_{si} = 19.23 °C, diffusion resistance 21.25 × 10^9 m/s, R 5.263 m^2.K/W. The theoretical thermal transmittance through the structure for both variants is shown in Figure 9.

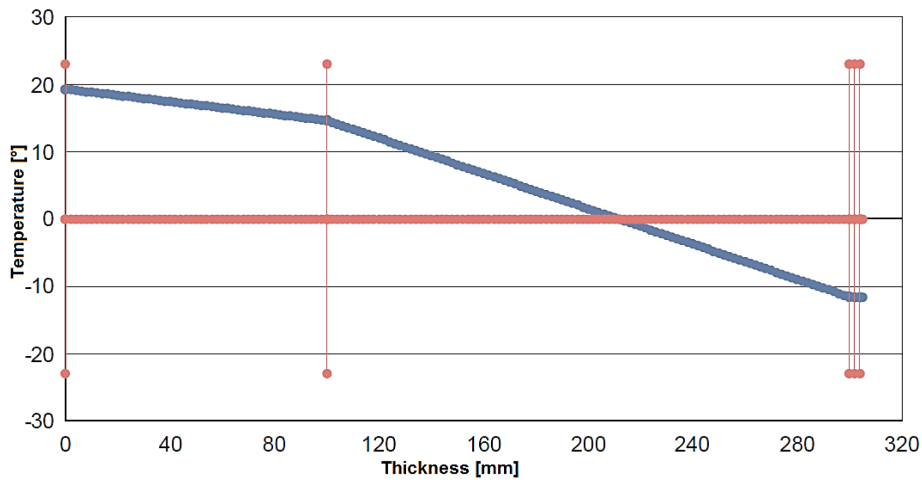

Figure 9. Theoretical thermal transmittance through the structure for variant A and variant B. (Notes: red color—zero values, blue color—temperature course in calculation models for both variants).

The differences between the computational simulations and the simulations in the laboratory in terms of the investigated thermal-technical parameters were as follows: variant A 60%, variant B 36.67%. The difference between the calculated variants of structures was 11.11% in terms of evaluated parameters.

3.2. Analysis of Acoustic Parameters of the Examined Design Variants

Measured data was processed with the software NorBuild. Measured and calculated results are shown in Figure 10. Evaluation is based on field measurement results obtained in one-third-octave bands by an engineering method.

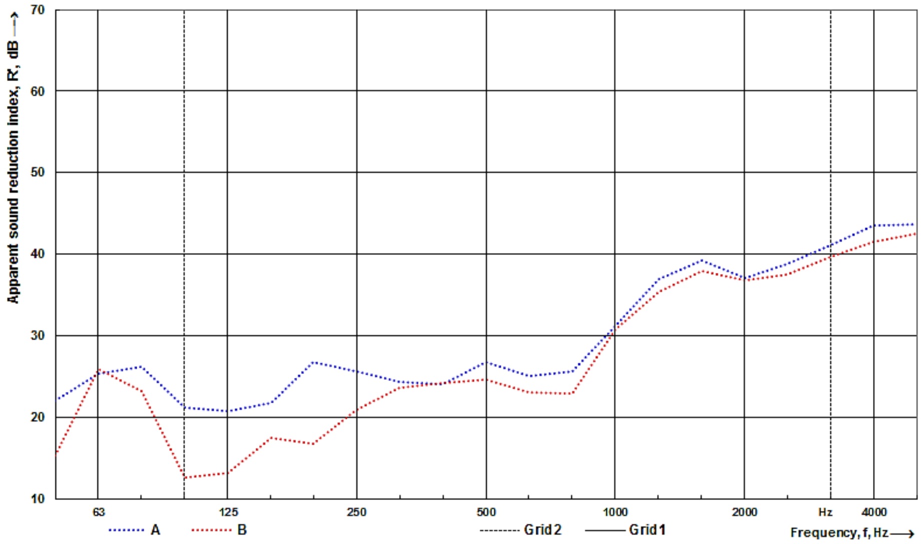

Figure 10. Measured and calculated results of acoustic analysis of both variants.

The sound reduction index of the red sample is 29 dB ($R'_w(C;C_{tr})$ = 29(−2;−5)) and blue sample is 31 dB ($R'_w(C;C_{tr})$ = 31(−1;−3)). We have to take into account that the partition element is not whole with sample material. Due to this reason, we expect better sound reduction indexes. These values we used are just for comparison of sound insultation. The blue sample reached better values for low frequencies in one-third-octave bands from 100–250 Hz. A significant difference between the compared samples can be observed up to approximately 500 Hz. These findings can be attributed to the fact that these were sandwich inhomogeneous samples of structures and thus the propagation of acoustic pressure at these frequencies is different in different materials.

According to [52,53], the so-called declared acoustic values of structures were determined for comparison of measurements in laboratory conditions as follows: variant A (Rw = 36), variant B (Rw = 38). By comparing laboratory measurements and calculated values, significant deviations were found in both variants.

4. Discussion

The constant advancement and development of new types of structural systems for wood-based constructions raises new research questions. New composite materials and various hybrid constructions are increasingly coming to the fore. One of the alternatives is constructions realized through cross laminated timber (CLT). These buildings ultimately compete with common building materials and technical solutions. Wooden buildings undoubtedly have many benefits but also barriers that can be innovated and improved by systematic research and verification. In the field of research on CLT structures, there are several works [54–58] focused mainly on technical properties. Fire safety of wooden buildings is also a very important part of the research of several scientific works [59–61]. The mentioned works mainly verify the influence of fires on the static stability of buildings and safety as such. A more detailed analysis of the structural details of CLT buildings was the subject of research by Chang et al. [62] where they investigated the differences of thermal bridges in comparison with classical construction solutions. CLT constructions are in some ways specific because they combine traditional material with a modern approach to composite solutions. In this mentioned area, the uniqueness of this solution is also in the fact that it shows very positive properties in terms of moisture migration, which is confirmed by the scientific work of Dong et al. [63]. Our findings obtained during our analyses and simulations also agree with the statements and conclusions of the mentioned research. Last but not least, it is now important to monitor the financial and energy balance of buildings during use. This work has addressed this area [64–66]. Based on the analyses performed in the mentioned scientific works, it is possible to conclude that wood-based buildings have a favorable energy balance in comparison to traditional buildings based on traditional materials. These studies are also confirmed by our research.

In addition to the fire resistance and energy efficiency of wood-based construction systems, one of the sensitive points of wood-based constructions is noise insulation. Therefore, the area is also given considerable attention acoustically in the context of wood-based constructions. The research work of Schoenwald et al. [67] within a multidisciplinary research project dealt with the investigation of acoustic properties of construction systems based on CLT prefabricated panels. The mentioned authors analyzed various variant solutions of floor and wall constructions of buildings. However, this work, unlike our scientific work, analyzed constructions by a different methodology. In this work, they investigated the effect of various methods as well as the possibilities of sound propagation through the structural details of the floor-wall contact. The conclusions show that the sound in these constructions spreads mainly directly through the structure on which it acts and only to a lesser extent through the details or contacts of the structures. From a certain conclusion of this work we find a parallel with our ideas, especially in the fact that it is not always possible to judge conclusions from one method of research or on the basis of only declared and calculated values. Because it is under laboratory conditions, different values than those declared are often demonstrated. From this point of view, an even more detailed analysis of this construction system based on prefabricated CLT panels is needed.

The work of the author Pérez [68] focused on the investigation and analysis of the acoustic properties of CLT structures used in building structures. This work also examined wall structures similar to our acoustic properties, also through a similar methodology. The conclusions of the work show that the sound spreads in structures where CLT prefabricated elements are used and through details, i.e., the joints of structures quite well. This means that it is necessary to prevent these ways of penetrating vibrations, for example by inserting different absorbent materials. This author states that absorbent materials at the joints can minimize vibration transitions in a significant way. In accordance with these conclusions, we state that in our analysis of the CLT prefabricated panel within the perimeter wall structure, we found that the paths where vibrations are transmitted are minimized in the compositions we analyzed. If we compare this with other design solutions, such as sandwich skeletal structures where there is a transmission of vibrations through the columns that intersect in CLT structures, such a negative phenomenon does not occur.

The analysis of acoustic properties of structures based on CLT prefabricated panels was also dealt with in the work of Di Bella et al. [69], Asdrubali et al. [70] and Pagnoncelli and Morales [71]. These works have a certain parallel in terms of certain knowledge in the field of determining the actual acoustic parameters of CLT prefabricated elements. In principle, they agree that it is not always possible to rely on the declared or calculated standard values of CLT-based structures in terms of their acoustic parameters. It follows that it is necessary to take into account and examine the behavior of structures in the laboratory and in-situ conditions, because such an examination at certain moments shows different values than the standard ones. Our ideas and knowledge also agree with these conclusions, because construction can behave differently in real conditions, which are influenced by a number of factors. Therefore, it is not desirable to just consider the calculated values, which are not always able to clearly take into account the surrounding conditions in specific situations. In addition, it is necessary to take into account the fact that each building is a unique work with specific properties.

5. Conclusions

Wood constructions have an increasingly strong position globally and in Europe thanks to their short constructions periods and better thermal-technical properties with comparable wall thickness. In view of the advent of ever new construction systems, especially wood-based systems, it is necessary to constantly explore this cloud. Therefore, the main goal of this research was focused on the investigation of selected structures by means of simulation models in laboratory conditions and also the structures were tested by means of computational models. The differences between the computational simulations and the simulations in the laboratory in terms of the investigated thermal-technical parameters were as follows: variant A 60%, variant B 36.67%. The difference between the calculated variants of structures was 11.11% in terms of evaluated parameters. In terms of acoustic properties, variant A showed better properties than variant B. The analysis of the acoustic parameters of the investigated variants also confirmed a significant difference between the declared and measured values. The analyses presented in this research show some differences in the comparison of the investigated states and computational models, therefore it is important to take into account several perspectives in the future when determining the parameters of such types of structures. It is necessary to thoroughly examine such design variants, which would contribute to cognition in this area of research into wood-based constructions.

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