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Selected aspects of designing pro-ecological buildings based on CLT

Wybrane aspekty projektowania proekologicznych budynków na bazie CLT

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Abstract. This paper presents aspects of designing pro-ecological buildings and the design criteria were characterized. The research problem includes determining selected aspects of design. The research method involves the analysis of pro-ecological conditions in architectural and construction design and the use of CLT materials and construction elements. This paper presents shear analogy methods and Gamma methods as selected examples of solving construction and material problems.

Keywords: ecological building; cross-laminated timber CLT; analytical methods; ecological considerations.

Streszczenie. W artykule zaprezentowano aspekty dotyczące projektowania budynków proekologicznych i scharakteryzowano kryteria projektowania. Problem badawczy obejmuje określenie wybranych aspektów projektowania. Metoda badań polega na analizie uwarunkowań proekologicznych w projektowaniu architektoniczno-budowlanym oraz zastosowania materiałów i elementów konstrukcyjnych CLT. W artykule zaprezentowano metody analogii ścinania i Gamma jako wybrane przykłady rozwiązywania problemów konstrukcyjno-materiałowych.

Słowa kluczowe: budynek proekologiczny; drewno klejone krzyżowo CLT; metody analityczne; uwarunkowania proekologiczne.

Environmental standards play a major role in building design, as more and more buildings aspire to be certified. An analysis of the methods of multi-criteria evaluation of buildings on the basis of which pro-environmental certificates are issued, their scope and popularity for use in the world, including Poland, is presented in monograph [1]. These methods are diverse, but cover issues such as: integration of the building with the environment; water and wastewater management; energy and atmosphere; raw materials and materials; environmental friendliness and comfort. All these criteria should be analysed and evaluated in the building design process. The use of appropriate raw materials and materials is important. Eco-friendly construction uses natural, renewable and easily recyclable materials, which are becoming increasingly popular. Timber structures, which are commonly used as a substitute for steel and concrete structures, minimise environmental impact due to their not great carbon footprint and therefore contribute to sustainability [2, 3], but their use is limited, especially for tall buildings [2, 4 ÷ 9]. In 2012, a 9-storey timber CLT building with a height of 32.2 m was constructed in Australia. Comparing it to equivalent reinforced concrete structures, carbon dioxide emissions were reduced by 1451 t [6, 7]. In 2017 The University of British Columbia in Canada constructed an 18-storey building with a height of 54 m. The use of prefabricated cross-laminated timber elements reduced construction waste by two-thirds and reduced carbon dioxide emissions by 2432 t compared to reinforced concrete structures [5, 7]. In the future, modern timber CLT structures could play an important role in reducing carbon emissions.

The aim of the analysis presented in this paper is to show that contemporary CLT-based design influences the environmental quality of a building and the quality of life of its occupants [1, 10]. It involves identifying selected aspects of sustainable design. The research method is based on the analysis of ecological considerations, the determination of the resulting design criteria and the use of cross-laminated timber structures in CLT technology. Selected aspects of the design of environmentally friendly buildings based on CLT concerning architectural-urban and structural issues are discussed. It should be emphasised that the process of designing and evaluating environmentally friendly buildings is multi-criteria [11].

Design criteria derived from ecological considerations

The determinants of environmentally friendly building design have been written about in many publications [1 ÷ 30]. The problems analysed include diverse criteria resulting from ecological considerations concerning [1, 10, 11]: site selection and location of the building; communication;

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energy efficiency; water and sewage management efficiency; efficiency in the use of materials and raw materials and their pro-environmentality. These criteria are discussed in detail in [1, 10, 30].

Efficiency in the use of materials and raw materials. The scope of material and raw material issues to be assessed should include the use of: environmentally friendly materials, natural, recycled, renewable, indigenous materials with low embedded energy and the elimination of materials containing toxic substances. The aforementioned prerequisites are met and increasingly used by CLT cross-laminated timber, e.g. produced as large-format building elements. CLT panels are often made of spruce, less commonly pine or other coniferous wood [2]. It is usually made up of three to seven layers [9], glued together, in all directions, with a polyurethane or melamine adhesive that meets stringent standard requirements for formaldehyde emissions. CLT panels are safe for health during production and use. The individual layers are additionally joined by so-called finger joints. The panels can be used in vertical and horizontal support structures, as they have good mechanical properties [2, 5, 10].

The problem of the carbon footprint. An important aspect influencing climate quality and environmental considerations in building design is the so-called carbon footprint. Building with a low carbon footprint is based on local materials.

We divide the carbon footprint into embedded in materials and operational carbon footprint, which arises during the use of the building, i.e. heating, cooling or electricity use. The type of material and the energy intensity of the production process are important. Various methods are available to assess the size of the carbon footprint. An interesting assessment of the entire life cycle of a building was presented by Giesekam [12]. In [13], the same buildings built with traditional, timber and passive wood technology were compared. The research and analysis concluded that wooden buildings have the smallest carbon footprint and the most favourable climate from a human point of view. Publications for designers, contractors and investors contain data demonstrating the advantages of glulam with CLT technology over other building materials. Reference is made to research carried out at Bangor University in Wales, which shows, among other things, that during the erection of a concrete building emits on average as much as 992 t of CO_2 into the atmosphere. A timber structure, on the other hand, produces none, storing as much as 426 t of CO_2 through carbon storage in wood. This means that the net effect of using timber technology instead of concrete is 1418 t less CO_2 in the atmosphere. CLT cross-laminated timber buildings are environmentally friendly and sustainable. For these reasons, it was chosen to be used in the design process of the buildings analysed.

Analytical methods in the design of environmentally friendly CLT timber structures

Currently in Europe, we do not have a single universally accepted approach to the structural analysis of cross-laminated timber. The revised EN 1995-1-1 will probably only include defined guidelines for the design of timber structures, including the CLT and LVL calculation methods. Therefore, the paper presents **the shear analogy method and the Gamma method** as an example of solving structural and material problems in the design of environmentally friendly buildings based on CLT. Several analytical methods have been discussed in the world literature, which include: Gamma (mechanically composite beam theory); composite theory (k-method); shear analogy (Kreuzinger method); Timoshenko beam theory [3, 27]. Examples of, inter alia, experimental, analytical and numerical studies of wooden reinforced members are presented in [31 ÷ 33].

The Gamma method [25 ÷ 27] assumes that the panel load is carried only by the longitudinal layers, while the shear stress is carried by the transverse layers. A factor γ is introduced to determine the effectiveness of the transverse layer connection. The relationship between the shear stress τ and the shear force V is expressed by equation (1):

$$\tau = \frac{(EQ)V}{(EI)_{eff}\,b} \qquad (1)$$

where:

$(EI)_{eff}$ – equivalent flexural stiffness calculated according to formula (2):

$$(EI)_{eff} = \sum_{i=1}^{n} (E_i I_i + \gamma_i E_i A_i k_i^2) \qquad (2)$$

where:

E_i – modulus of elasticity of the i-th layer in the longitudinal direction of the beam;

EQ – equivalent static moment;

I_i – moment of inertia of the cross-section of the i-th layer;

A_i – cross-sectional area of the i-th layer;

k_i – distance of the centre of gravity of the cross-section of the i-th layer from the centre of gravity of the cross-section;

γ_i – the joint efficiency factor of the i-th layer, which can be determined according to the formula:

$$\gamma_i = \left(1 + \frac{\pi^2 E_i b_i h_i}{L_{eff}^2 G_{rj}\, b_j / h_j}\right)^{-1} \qquad (3)$$

where:

L_{eff} – effective beam length;

b_i; h_i – the width and height, respectively, of the i-th longitudinal layer;

G_{rj} – shear modulus for the jth transverse layer connecting the i-th longitudinal layer;

b_j; h_j – the width and height of the j-th longitudianl layer.

$$(EQ)_5 = \gamma_1 E_0 bh(h + h_1) + $$
$$+ 1/2E_{90} bt(h + h_1) + 1/8\gamma_2 E_0 bh^2 \qquad (4)$$

Figure 1 shows an equivalent cross-section of a 5-layer beam.

The shear analogy method assumes that a layered panel is an apparent section consisting of two beams A and B. Beam A provides the bending stiffness of the individual layers along its own axis, while beam B provides the bending and shear stiffness of all layers. The beams are connected by an auxiliary web – a connecting element with infinite axial stiffness. Therefore, it is necessary to check equal deformation at any point along the beam due to the fact that it carries a lateral load.

For a CLT slab with longitudinal layers, the elastic modulus parallel to the fibres E_i, the width b_i and thickness h_i and the equivalent bending stiffness $(EI)_A$ and $(EI)_B$ can be determined from the formulae:

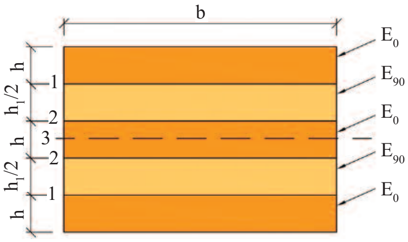

Fig. 1. Equivalent section for 5-layer CLT beam
Rys. 1. Przekrój zastępczy belki 5-warstwowej CLT

$$(EI)_A = \sum_{i=1}^{n} E_i b_i \frac{h_i^3}{12} \qquad (5)$$

$$(EI)_B = \sum_{i=1}^{n} E_i A_i k_i^2 \qquad (6)$$

where:
$A_i = b_i h_i$ – cross-sectional area of the i-th longitudinal layer;
k_i – distance of the centre of gravity of the cross-section of the i-th layer from the centre of gravity of the cross-section.

Therefore, the force or moment must be proportionally transmitted through beams A and B according to their equivalent stiffness in bending and therefore the shear force $V_{A,\,i}$ transmitted through the i-th layer of beam A is determined by the formula:

$$V_{A,i} = \frac{E_i I_i}{(EI)_A} V_A \qquad (7)$$

where:
V_A – shear force transmitted by beam A.
The shear stress of each individual beam layer A, $\tau_{A,i}$ can therefore be determined from the formula:

$$\tau_{A,i} = \frac{3}{2bh_i} \frac{E_i I_i}{(EI)_A} V_A \qquad (8)$$

where:
$I_i = b_i h_i^3/12$ – moment of inertia of the i-th longitudinal layer.

Beam shear stress B, $\tau_{Bi,i+1}$ determines the formula:

$$\tau_{B,i+1} = \frac{V_B}{(EI)_B} \sum_{j=i+1}^{n} E_j A_j k_j \qquad (9)$$

where:
V_B – shear force transmitted by beam B.

By determining the shear in the plane perpendicular to the CLT panel fibres, the maximum shear force carried by the beam B can be calculated from equation (9) by substituting $\tau_{B,i+1}$. The shear resistance of the beam can therefore be determined from equation (10):

$$V = V_B \left[1 + \frac{(EI)_A}{(EI)_B} \right] \qquad (10)$$

Selected designs of environmentally friendly buildings based on CLTs

As a result of the analyses and based on sustainable building models [1, 10], students under our supervision developed CLT-based designs for environmentally friendly buildings (Figures 2 and 3). The selection of the location of the buildings and the use of existing site conditions [1] were optimised. Buildings were designed to be integrated into existing and designed greenery. Renewable energy sources such as photovoltaics; mini-wind turbines; heat pumps; recuperation and computer control of the building infrastructure were used. The main structural and architectural materials were CLT cross-laminated timber elements, which provided the buildings with environmentally friendly qualities and gave them an original architectural form. The high strength or stiffness of CLT elements is comparable to steel and much better than concrete elements. This is related

Fig. 2. Design of the Bioclimatic modular unit – as a spatial dominant
Fig. A. Hajdenrajch
Rys. 2. Projekt bioklimatycznej jednostki modularnej – jako dominanty przestrzennej
Rys. A. Hajdenrajch

Fig. 3. Design of a service and commercial facility integrated with nature
Fig. J. Maciantowicz
Rys. 3. Projekt obiektu usługowo-handlowego zintegrowanego z przyrodą
Rys. J. Maciantowicz

to the process by which the natural structural variability and heterogeneity of natural wood is eliminated [29]. The low stiffness at the joints of the elements or the low weight of the material can cause movements on the higher floors of the building. These can be eliminated by precise preparation of the prefabricated timber structure elements and correct assembly on site.

An important consideration in the design process is concern for the environment. Studies [28, 29] have confirmed that replacing concrete and steel with natural materials can reduce CO_2 emissions by up to 15 – 20%. An obstacle to the realisation of tall and high-rise buildings in Poland, as in other countries, is building regulations. Many companies and organisations associated with the promotion and realisation of wood element construction have carried out tests on the fire resistance of glulam. It was found that sandwich panels can achieve a fire resistance class of EI30, which is determined by the number of timber layers used. Additional protection of the wooden structure can be provided by encapsulation, i.e.

cladding the wooden elements with, for example, two layers of gypsum boards.

Summary

This paper presents selected aspects of the design of environmentally friendly buildings on a CLT basis. The activities carried out by the designers using the model and the developed evaluation method in the aspect of designing pro-environmental buildings yielded satisfactory solutions. The model illustrating the method and the building evaluation criteria with their valuation presented in [1] were used to develop the design task. The relevance of the proposed assessment criteria was confirmed and applied in the design process. The developed method can be used in the design process of environmentally friendly and sustainable buildings that meet societal expectations [30].

The ecological aspect of the project should include analyses concerning: site selection and location of the facility; communication; energy efficiency; water and sewage efficiency; efficiency in the use of materials and raw materials and their environmental friendliness.

An important problem is the selection of an environmentally friendly material and construction solution. In the examples analysed, structures made of CLT cross-glued timber elements, among others, were used. Examples of tests of glued structural elements are presented, among others, in [31 ÷ 37]. The paper presents the selected method of dimensioning the elements. The analysed designs of pro-ecological buildings are positive examples of the architecture of the future. The methods used in their design process represent an unquestionable advance in the shaping of CLT-based pro-environmental buildings. Architectural and building designs should be made with concern for the quality of our environment and meet social needs.

References

[1] Kamionka L. Architecture in a Sustainable Environment. The Future Begins Today. Monography, Architecture 16, Kielce University of Technology, Kielce. 2021,

[2] Dobeš P, Lokaj A, Vavrušová K. Stiffness and Deformation Analysis of Cross-Laminated Timber (CLT) Panels Made of Nordic Spruce Based on Experimental Testing, Analytical Calculation and Numerical Modeling. Buildings. 2023; https://doi.org/10.3390/buildings13010200.

[3] Svortevik VJ, Engevik MB, Kraniotis D. Use of cross laminated timber (CLT) in industrial buildings in Nordic climate – A case study. IOP Conf. Ser. Earth Environ. Sci. 2020, 410, 012082.

[4] Van De Kuilen JWG, Ceccotti A, Xia Z, He M. Very tall wooden buildings with cross laminated timber. Procedia Eng. 2011, 14, 1621 – 1628.

[5] Brandner RJ, Flatscher G, Ringhofer A, Schickhofer G. Thiel, Cross laminated timber (CLT): Overview and development. Eur. J. Wood Prod. 2016, 74, 331 – 351.

[6] Luyue Yan, Yi Li, Wen-Shao Chang, Haoyu Huang. Seismic control of cross laminated timber (CLT) structure with shape memory alloy-based semi-active tuned mass damper (SMA-STMD). Structures. 2023; https://doi.org/10.1016/j.istruc.2023.105093.

[7] Woodsolutions. Forte Living. 2023; Available from: https://www.woodsolutions.com.au/case-studies/forte-living.

[8] United Nations. Circularity concepts in wood construction ed. C.o. F.a.t.F. Industry. 2022, Geneva: United Nations.

[9] EAD 130005-00-0304 solid wood slab element to be used as a structural element in buildings, March 2015.

[10] Kamionka L, Wdowiak-Postulak A, Hajdenrajch A. Nowoczesne budownictwo drewniane w technologii CLT na przykładzie budynku Bioklimatycznej Jednostki Modularnej. Materiały Budowlane. 2022, 3 (595):

[11] Niezabitowska E, Masły D. Ocena jakości środowiska zabudowanego i znaczenie dla rozwoju koncepcji budynku zrównoważonego, Gliwice. 2007.

[12] Giesekam J. Reducing carbon in construction: a whole life approach. April 2018. Leeds: CIE-MAP.

[13] Jae-Won Oh, Keum-Sung Park, Hyeon Soo Kim, Ik Kim, Sung-jun Pamg, Kyung-San Ahn, Jung-Kwon Oh. Comparative CO_2 emissions of concrete and timberslabs with equivalent structural performance. Energy and Buildings. Volume 281.2023.

[14] Baranowski A. Projektowanie zrównoważone w architekturze, Gdańsk, Wydawnictwo Politechniki Gdańskiej. 1998.

[15] Stawicka-Wałkowska M. Budownictwo przyjazne środowisku naturalnemu w aspekcie strategii zrównoważonego rozwoju. Sekcja Fizyki Budowli, Komitet Inżynierii Lądowej i Wodnej PAN, Łódź. 2011.

[16] Panek A. E-Audyt metoda oceny oddziaływania na środowisko obiektów budowlanych, Warszawa 2002.

[17] Schneider-Skalską G. Zrównoważone środowisko mieszkaniowe. Społeczne – oszczędne – piękne, Kraków. 2012.

[18] Jagiełło-Kowalczyk M. Dom zrównoważony – energooszczędny – ekologiczny – trwały. Kraków. 2019.

[19] Horn P. Zrównoważony rozwój w procesie kształtowania współczesnego osiedla. Idee, przykłady, Wydawnictwo Politechniki Wrocławskiej. 2019.

[20] Augustyn A. Zrównoważony rozwój miast w świetle idei Smart City. Wydawnictwo Uniwersytetu w Białymstoku, 2020.

[21] Browinind WD, Barnett DL. A primer on Sustainable Building, 1995.

[22] Anink D. Handbook of Sustainable Building. 1996.

[23] Bennets H, Redford A, Bennets H. Understanding Sustainable Architecture. 2004,

[24] Bott G, Grassl S, Anders Bott H, Grassl G, Anders S. Sustainable Urban Planig. Vibrant Neighbourhoods-Smart City-Resilience. Detail 2019.

[25] Zirui Huang, Lingyun Jiang, Chun Ni and Zhongfan Chen. The appropriacy of the analytical models for calculating the shear capacity of cross-laminated timber (CLT) under out-of-plane bending. Journal of Wood Science (2023) 69:14, https://doi.org/10.1186/s10086-023-02089-y.

[26] Poński M, Paluszyński J. Wymiarowanie elementów zginanych wykonanych z drewna klejonego krzyżowo (CLT) w ujęciu PN-EN 1995-1-1.Budownictwo o Zoptymalizowanym Potencjale Energetycznym, Vol. 7 Nr 2, 2018. Wydawnictwo Politechniki Częstochowskiej.

[27] PN-EN 1995-1-1. Eurokod 5. Projektowanie konstrukcji drewnianych. Część 1-1: Postanowienia ogólne. Reguły ogólne dotyczące budynków.

[28] Dmitruk M. Zastosowanie drewna klejonego w konstrukcji budynków wysokościowych, na przykładzie realizacji z krajów zachodnich. TEKA 2020, Nr 2 Komisji Architektury, Urbanistyki i Studiów Krajobrazowych Oddział Polskiej Akademii Nauk w Lublinie. https://orcid.org/0000-0002-6368-4206.

[29] Cornwall W. Would you live in a wooden skyscraper. Science. 2016. https://www. sciencemag. org/news/2016/09/would-you-live-wooden-skyscraper stan na dzień 27.03.2020.

[30] Kamionka L. Multi-criteria assessment methods and their impact on the ecologicalquality of the built environment/Metody wielokryterialnej oceny i ich wpływ na jakość ekologiczną przestrzeni zabudowanej. Urbanism and Architecture Files of Polish Academy of Sciences Krakow branch, tom/volume LI 2023. Teka Komisji Urbanistyki i Architektury. Oddział PAN w Krakowie.

[31] Wdowiak-Postulak A, Świt G, Dziedzic-Jagocka I. Application of Composite Bars in Wooden, Full-Scale, Innovative Engineering Products – Experimental and Numerical Study. Materials. 2024; 17 (3), 730; https://doi.org/10.3390/ma17030730.

[32] Wdowiak-Postulak A. Numerical, theoretical and experimental models of the static performance of timber beams reinforced with steel, basalt and glass pre-stressed bars. Composite Structures. 2023; Vol. 305, 116479; https://doi.org/10.1016/j.compstruct. 2022.116479.

[33] Wdowiak-Postulak A. Basalt Fibre Reinforcement of Bent Heterogeneous Glued Laminated Beams. Materials. 2021; 14 (1), 51; https://doi.org/10.3390/ma14010051.

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