Marek Wieruszewski[1], *Bartłomiej Mazela*[2]

Cross Laminated Timber (CLT) as an Alternative Form of Construction Wood

Lamelirano drvo (CLT) kao alternativni oblik drva za gradnju

Review paper • Pregledni rad
Received – prispjelo: 24. 4. 2017.
Accepted – prihvaćeno: 1. 12. 2017.
*UDK: 630*833.01*
doi:10.5552/drind.2017.1728

ABSTRACT • *Wood, which is a natural and renewable material, is gaining increasing appreciation again and it is more and more commonly used in the building industry. The use of wood has been improved due to the application of modern bonding technologies (e.g. Glued Laminated Timber, Cross Laminated Timber), the development of modern production technology and improved methods of wood protection from fire. As large-size assortments of constructional timber in the form of light beams and boards are available on the market, it is possible to make stable and durable joints between individual constructional elements of a building. Among wood materials used for construction, CLT is increasingly used. It is applied in the construction of single-family houses, residential buildings, multi-storey buildings, public buildings, industrial and retail buildings as well as bridges. CLT was developed as a result of European research how to use short wood, left after the elimination of faults, for private construction. The trend very soon spread to the building industry in North America, Australia and Japan. CLT was more and more commonly used in multi-storey buildings due to its higher seismic resistance. At the beginning of the 30-year history of CLT, the use of this building material was minimal. However, due to the ecological trend and a wide range of economic factors (the value of material used and costs of production combined with high precision of finished products), this technology gained significant popularity. The surge of interest in wooden constructions also resulted from better distribution channels and technical approvals for different concepts of wooden construction boards. The following countries are leaders in the production and use of CLT: Austria, Germany, Switzerland, Sweden, Norway and the United Kingdom. In recent years, New Zealand and Australia have joined this group. CLT boards are exported to North America, Japan and Russia. The surge of producers and investors' interest in CLT boards results from the production process diversity and construction variability. In consequence, there is an increasing number of concepts specifying the range of product application, depending on its strength and resistance.*

Key words: *wood construction material, Cross Laminated Timber*

SAŽETAK • *Drvo kao prirodni i obnovljivi materijal ponovo dobiva sve veću vrijednost i sve se češće upotrebljava u graditeljstvu. Upotreba drva poboljšana je zbog primjene suvremenih tehnologija vezanja (npr. lamelirano drvo), razvoja suvremene proizvodne tehnologije i poboljšanih metoda zaštite drva od požara. Budući da je ponuda građevnog drva u obliku laganih greda i ploča na tržištu velika, njime je moguće izvesti stabilne i izdržljive spojeve među pojedinim konstrukcijskim elementima zgrade. Među drvnim materijalima koji se rabe za gradnju sve je zastupljenije unakrsno lamelirano drvo (CLT). Primjenjuje se u izgradnji obiteljskih kuća, stambenih zgra-*

---

[1] The author is assistant professor at the Department of Wood-based Materials, Faculty of Wood Technology, Poznan University of Life Sciences, Poznań, Poland. [2]The author is professor at the Institute of Wood Chemical Technology, Faculty of Wood Technology, Poznan University of Life Sciences, Poznań, Poland.

[1] Autor je profesor Odsjeka za materijale na bazi drva, Fakultet drvne tehnologije, Sveučilište bioloških znanosti u Poznanju, Poljska. [2]Autor je profesor Instituta za kemijsku tehnologiju drva, Fakultet drvne tehnologije, Sveučilište bioloških znanosti u Poznanju, Poljska.

da, višekatnica, javnih zgrada, industrijskih i maloprodajnih zgrada, kao i mostova. CLT je razvijen kao rezultat europskih istraživanja uporabe drvnih elemenata malih dimenzija, preostalih nakon uklanjanja grešaka drva, i to mahom za privatnu gradnju. Trend se vrlo brzo proširio na građevnu industriju u Sjevernoj Americi, Australiji i Japanu. CLT se zbog svoje velike seizmičke otpornosti sve više upotrebljava u višekatnim zgradama. Na početku sada već 30-godišnje povijesti CLT-a uporaba toga građevnog materijala bila je minimalna. Međutim, zbog ekološke prihvatljivosti i širokog spektra ekonomskih čimbenika (cijena upotrijebljenog materijala i troškovi proizvodnje, u kombinaciji s velikom preciznošću gotovih proizvoda) ta je tehnologija postigla veliku popularnost. Osim toga, sve veće zanimanje za drvene konstrukcije rezultat je i boljih distribucijskih kanala te dobivanja tehničkih odobrenja za različite koncepte drvenih građevnih ploča. U proizvodnji i upotrebi CLT-a vodeće su zemlje Austrija, Njemačka, Švicarska, Švedska, Norveška i Ujedinjeno Kraljevstvo. U posljednjih nekoliko godina toj su se skupini zemalja pridružili Novi Zeland i Australija. CLT ploče izvoze se u Sjevernu Ameriku, Japan i Rusiju. Povećanje broja proizvođača i zanimanje ulagača za CLT ploče rezultat je raznolikosti proizvodnih procesa i varijabilnosti gradnje. Stoga postoji sve veći broj koncepata koji određuju raspon primjene proizvoda, ovisno o njegovoj čvrstoći i otpornosti.

Ključne riječi: *drvni građevni materijal, unakrsno lamelirano drvo*

1 INTRODUCTION
1. UVOD

Wood, as one of natural and renewable materials used by man, has gained more and more recognition and applications in construction. Over the last 30-years Europe has seen a considerable increase in the share of laminated wood in building structures. One should mention here not only the use of GLT (Glued Laminated Timber), but also CLT (Cross Laminated Timber) produced in the form of panels. As soon as such assortments of structural wood emerged on the construction market, they were quickly used at the mass scale and included in the European standards connected with construction in the private and public sectors. CLT manufactured in the form of light panels is a multilayer wooden panel, where every layer is arranged at right angle to the adjacent layers. This assures the appropriate rigidity and stability of final material. CLT panels are usually made of three to seven layers; typically there is an odd number of layers arranged symmetrically to the middle layer. The joints between the individual layers of structural timber owe their stability and strength to the application of suitable, ecological glues. Amongst the composite wood materials used for structural purposes and in comparison to traditional building materials, CLT is a product characterised by many advantages, of which the most important are:

- sustainable consumption of raw material used for its production;
- an energy-efficient production process, which makes the material environmentally friendly;
- superb static, mechanical and insulation properties;
- lightness, which makes the building structure incomparably lighter than other structures made of conventional materials;
- the possibility of producing prefabricated elements, which results in a short time of completion of the whole building regime;
- the possibility of combination with other building materials (steel, glass, plastics, etc.), resulting in maximum freedom of architectural design.

The above-mentioned advantages make the CLT application range very broad, i.e. from single-family houses and residential buildings, through multi-storey public buildings, to industrial and commercial buildings, and even bridge structures.

Hitherto in Europe CLT has been primarily a material used for construction of low buildings, i.e. one- or two-storey houses. Despite the growing popularity of CLT in single-family housing, more and more often it is also used to accomplish more ambitious tasks of erecting multi-storey buildings, where it is the basic construction material, e.g. a seven-storey Stadthaus condominium in London (2008), a ten-storey residential building in Melbourne (2012), and a fourteen-storey high rise in Bergen (2015). The latest project is a USA design –Owings and Merrill Company designed a forty-two-storey condominium. In some regions, buildings made of CLT enjoy special interest due to their enhanced seismic endurance (Popovskii *et al.*, 2010; Pei *et al.*, 2010, 2012).There are many reasons why wood is better than any other building material. The most important is sequestration and accumulation of carbon dioxide, the fast pace of structure building, compatibility with other materials (Risen 2014). Steel, glass and concrete revolutionised the 19th and 20th century construction. De Rijke believes that wood will do the same for the 21st century construction, and that wooden buildings made of CLT are the future.

2 WOOD COMPOSITES
2. DRVNI KOMPOZITI

The initial development and success of CLT was connected to the first analyses of the use of multi-layer timber in roof structures (Cziesielski, 1974). Further efforts to introduce composite wood materials into construction were made in the period 1981-1989. Those efforts were supported by numerous studies conducted in Lausanne and Zürich at the beginning of 1990 (Colling, 1990; Colling *et al.*, 1992; Frampto and Cava, 1995). The modern CLT technology started to develop rapidly after 1996 in Austria as a result of cooperation between industry and science. For the first few years the development of wood panel application was progressing slowly (Espinoza *et al.*, 2015). At the beginning of 2000, the demand for CLT increased thanks to green building, which was developing at that time. The high efficiency of wood material processing and favourable changes of regulations had a positive effect on the development of that technology (Brandner, 2014; Brandner *et al.*, 2016; Pavlyukovskiy, 2012). Those factors directly translated into CLT production, which amounted to approximately 600 000 m^3 in 2014, only to exceeded 1 million m^3 in successive years and maintain an upward trend (Muszyński, 2015; Plackner, 2015). A significant factor limiting the use of CLT in building systems in the European Union was the requirement to obtain European Technical Assessment certificate (ETA). The basic standards define the requirements for CLT wooden structure cover of multi-family residential buildings and public buildings (Augustin *et al.*, 2010; Zumbrunnen and Fovargue, 2012). Austria, Germany, Switzerland, Sweden, Norway, and the United Kingdom are the countries leading in terms of CLT production and application (Schickhofer, 2010). In recent years, a rapid growth of CLT production and use has been recorded in North America (Canada and the United States), as well as in Japan, Taiwan, New Zealand (Crews, 2011; Lewis *et al.*, 2014), and Russia (Vdovin and Karpov, 1999; Pilagin, 2006). The development of CLT construction has also been observed in China and Australia, countries that import CLT from Europe.

It is worth mentioning that the CLT system is also known as "X-lam" ("cross lam"), "plywood boards" (PBs), and "Massivholz". The main European manufacturers of CLT are Austrian, German, and Scandinavian companies (Tab.1).

Each of the presented companies uses a similar production process, whose core stage is procurement and quality sorting of timber. Those activities largely come down to the assessment of the strength properties of timber. The production process also encompasses the manner of joining boards into panels, which are a semi-product for further production of panels, whose adjacent layers are arranged at right angle to one another, thus wood grain is cross-arranged. Significant technological differences between the individual producers primarily come down to the thickness of manufactured layers, their strength class, and the systems of joining timber in terms of length, width and thickness. Glues and limit dimensions of the obtained elements also play an important role (Falk, 2010, 2011; Brandner and Schickhofer, 2008, 2010, 2012; Brandner, 2014; Brandner *et al.*, 2016).

Recently, research on the properties of CLT panels and their use in structures has become very intensive, which results from current business conditions that have a direct effect on the increased interest in new wood materials and their possible applications in construction. Major advantages of the CLT technology encompass the use of fast-renewed resources and less contamination of the environment, compared to alternative materials,

Table 1 Comparison of technical specifications of CLT panels by producers
Tablica 1. Usporedba tehničkih specifikacija CLT ploča različitih proizvođača

Company *Proizvođač*	**Maximum panel dimensions, m** *Maksimalne dimenzije ploča,* m			**Classification of raw material** *Klasifikacija sirovine*	**Class of raw materials EN 1995-1-1** *Klasa sirovine prema EN 1995-1-1*	**Product name** *Naziv proizvoda*
	Maximum length *Maksimalna duljina*	**Maximum width** *Maksimalna širina*	**Maximum thickness** *Maksimalna debljina*			
KLH (Austria, United Kingdom, Sweden)	16.50	2.95	0.50	classification by EN 338 and EN 13017-1	EN 338 C24	KLH
Binderholz (Austria)	24	3.50	0.34	classification by DIN EN 13017-1	EN 338 C18/C24	BBS-125, BBS-XL
Martinsons (Sweden)	6	1.20	0.259	classification by NS- EN 13017-1	NS -EN 338 C14 – C24	KL-trä
Stora Enso (Austria)	16	2.95	0.32	classification by EN 14080	EN 338 C16/C24/C30	C-panels, L-panels
Thoma Holz GmbH (Austria)	8	3	0.80	classification by ETA - 13/0785	EN 338 C16 C24	H100
Finnforest Merk (Germany / United Kingdom)·	20	4.80	0.297	classification by EN 338 and EN 13017-1	EN 338 C24	-
HMS (Germany)	16	3.90	0.32	classification by EN 338 and EN 13017-1	EN 338 C24	-
NORDPAN SPA AG (Italy)	5	2.05	0.27	DIN EN 14081 DIN 4074-1	SK27/SK30	Nordpan
Züblin Timber Bauelemente (Germany)	7	3	0.31	DIN EN 14081 DIN 4074-1	EN 338 C24	LENO
LIGNOTREND AG (Germany, Switzerland)	18	0.625	0.247	DIN EN 14081 DIN 4074-1	EN 338 C20/24	LIGNO HBV

Source: Technical Approval No. Z-9.1-209, Z-9.1-482, Z-9.1-501, Z-9.1-534, Z-9.1-555, Z-9.1-574, Z-9.1-602, Z-9.1-559, Z-9.1-640 which is connected with the production technology. A review of literature on CLT suggests that the research concerns primarily the following matters:

- determining the mechanical properties of CLT (Massivträ: Handboken, 2006; Brandner and Schickhofer, 2008, 2012; Stürzenbecher, 2010; Falk and Buelow, 2011);
- defining possible applications of CLT as structure members of hybrid multi-storey buildings (Falk, 2011);
- searching for new methods of joining both panels and ready products in the assembly process (Follesa *et al.*, 2010);
- performance of CLT structures during seismic vibrations (Bogensperger *et al.*, 2010, 2011);
- determining the durability of CLT structures subjected to fire (Frangi *et al.*, 2009);
- determining the resistance of CLT panels to other destructive factors (Werner and Richter, 2007).

Nevertheless, most of research and studies on CLT concern technical verifications (Massivträ: Handboken, 2006; Bejder *et al.*, 2010, 2011, 2012). CLT panel elements assure that applications are multipurpose within the designed structure thanks to the improved technical properties, as confirmed by a series of tests (Gold and Rubik, 2008; Roos *et al.*, 2010). In terms of the product's aesthetics (Bell, 2006), there are many possible modifications of the product, which allow considerable elimination of natural flaws found in the initial raw material (Fragiacomo, 2014; van de Lindt *et al.*, 2013).

Taking into consideration the technical possibilities provided by the wood industry as regards large-scale CLT production as well as considerable dimensions of the offered products (thickness up to 0.5m, width up to 4m, and length up to 20 m), it could be said that building engineering has been given a new material, which has made it possible to use solid wood in a mass-scale construction to a much greater extent than before. Apart from the technical advantages of CLT panels in terms of design, the major asset of this material is the low cost of structural timber processing, i.e. minimal cost prior to gluing. Although sawing of raw material to obtain 16-40 mm thick timber entails some loss of material, taking into consideration the available sections of logs, such sawing allows the use of so-called side boards, hitherto considered by-product.

The logistics of building structure erection is also of importance. The wall and floor panels may be produced with a high degree of prefabrication, which assures not only a material cost decrease, but also a shortened construction period.

In terms of structural functions, CLT panels may be divided into the following types:

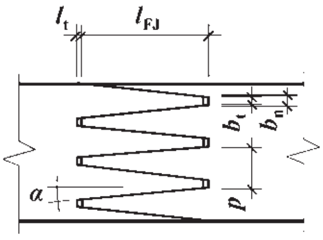
- panels intended for ceilings and floors, designed to bear the structure-specific load, where the main direction of load is perpendicular to the axis of the panel middle layer;
- panels intended for structural members of walls, designed to bear the loads resulting from, inter alia, the height of the building, where the main direction of load is in line with, i.e. parallel to the axis of the panel middle layer;
- combined structures, based on 3-D arrangement, for three-dimensional projects forming the spaces of building using CLT panels, which bear loads in different directions.

3 MATERIAL AND TECHNOLOGY
3. MATERIJAL I TEHNOLOGIJA

A standard CLT panel is composed of 12 ÷ 45 mm thick timber (EN 16351). Currently, in the context of adopted standardization, the thickness of a CLT layer ranges from 20 to 40 mm (Z-9.1-482 2010, Z-9.1-559). Such thickness range is used, inter alia, by the producers in Austria and Germany. Further standardization, particularly as regards the mechanical properties of CLT, concerns the stresses within the plane (for application in ceiling, floor, and roof structures) and the internal structure (for application in walls). As regards those tests, it could be said that there is no upper limit of the panel width; however, due to the shear stresses occurring between the layers composed of minimum-width timber (40 ÷ 300 mm), the following standards were assumed: 0.6, 1.2, 2.25, 2.4, 2.7, and 2.95 m (maximally up to 4 m). Those assumptions are allowed for in the effective Technical Approvals. Special emphasis is placed on the assurance of identical thicknesses of all the layers making a CLT panel. This is connected to current assumptions that all CLT planes are exposed to the same transverse stresses. Some researchers have also conducted studies on changeable layer arrangements with the use of wood of various strength classes (Li, 2015; Li and Lam, 2016). In terms of strength classification, the use of the available assortments of timber with various thickness parameters and characterised by admissible standards, suggests higher strength parameters of CLT panels compared to the comparable groups of glued laminated timber GLT (table 3) (Thiel, 2014; Fragiacomo, 2014).

Presently, the main softwood species used by the European CLT producers is Norway spruce (*Picea abies*), also often found in association with silver fir (*Abies alba*). Apart from spruce and fir, the following species are also used: Scots pine (*Pinus sylvestris*), European larch (*Larix decidua*), Douglas fir (*Pseudotsuga menziesii*), and Swiss pine (*Pinus cembra*). The last two species are often used for the surface layer of CLT panel due to their high decorative values. It is possible to use other species as well, e.g. maritime pine (*Pinus pinaster*), harvested mainly in Sardinia (Italy), or the wood of deciduous species, as long as it fulfils the quality and strength criteria. An example of such species diversity in CLT panels are the structures erected within the project "massive_living" in Austria, where one of the buildings was completely made of wall elements using silver birch (*Betula pendula*). Further possibilities of using hardwood allow for poplar (*Populus spp.*), ash (*Fraxinus excelsior*), and other species, which are interesting in terms of wood harvesting for economic purposes in a given region (Z-9.1-721).

Table 2 Dimensions and finger joint profiles, and geometrical dimensions of a section acc. to the standard EN 387
Tablica 2. Dimenzije i profili zupčastih spojeva te geometrijske dimenzije spoja prema standardu EN 387

Finger length *Duljina zubaca*	**Pitch** *Korak*	**Width** *Širina*	**Base width** *Širina baze*	**Tip gap** *Zazor*	**Flank angle** *Kut zubaca*	**Loss in cross section** *Gubitak poprečnog presjeka*	
l_{FJ}	*p*	*bt*	*bn*	*lt*	*α*	*v(bn)*	
mm					°	%	
15	3.8	0.42	0.52	5	5.6	13.6	
20	5.0	0.50	0.60	5	5.7	12.0	
20	6.2	1.00	1.11	5	6.0	17.8	
50	12.0	2.00	2.48	3	4.6	20.7	

One of the parameters characterising raw material and determining its strength is density, which ranges from 480 to 500 kg/m^3 on average for CLT panels. This range corresponds to the density of softwood species intended for structural purposes. Thereby, the weight of typical CLT in a wall panel of a thickness of 103 or145 mm ranges from 67 to 72 kg/m^2 or 49 to 52 kg/m^2, respectively, (Ceccotti, 2010; Popovski, 2010; FPInnovations, 2010).

Correctly conducted heat treatment is an important element of the technological procedure for preparing structural raw material for CLT production. Due to the gluing processes and the conditions in which the final structure is used, wood for CLT production should be dried and conditioned until it reaches a technologically required moisture content of 12 ± 2%. The prepared material is then classified in terms of strength in the process of optical or/and mechanical sorting in accordance with the standard EN 14081-1 or, in the case of German producers, the standard DIN 4074-1. This is of utmost importance considering typical production requirements for CLT panels, where all pieces of timber within a layer should be of the same species and strength class (Schickhofer, 1994; Wathén, 2006; Augustin *et al.*, 2010). In other cases, where various species of wood are used, the defined strength of a single layer used for panel manufacture should be reduced to the lowest class of the timber used. A system of structural timber classification currently used in Europe is based on timber bending strength. According to the system, timber is classified in the range from C16 toC40 (acc. to EN 338). The system was defined for solid softwood and falls within a range of 16-40N/mm^2. According to the requirements of the European Technical Assessment, timber of class C24 is usually used in the production of CLT panels of homogenous structure. At the same time, 10 to 30 % of layers located closer to the middle of the panel can be of lower strength class, which does not result in worsening of the CLT mechanical properties (DIN 4074-1:2012-06). In the case of combined CLT panels, the surface layer is manufactured of timber of the strength class C24 and the transverse inner layer is made of C16/C18 timber. In reality, the assumed load bearing capacity of CLT in bending is connected with the strength of the outer layers (EN 384). Strength stability observed in the plane of CLT panel stems from the composition and properties of transverse layers, which make up a cross arrangement. Based on the available test results, it was ascertained that the strength properties of products belonging to the GLT or CLT system stabilise in comparison to initial material, i.e. solid wood, which has often numerous structural flaws. The process of flaw elimination consists in the elimination of so-called inadmissible sections from the transverse structural materials. Next, those materials are joined in length using finger joints of specific finger lengths defined for GLT and CLT (table 2). The prepared timber elements, which have been classified and optimised for the production of glued timber, are milled to obtain finger joints of a finger length ranging from 15 to 20 mm. To obtain strong joints, facilitating the obtainment of a desired strength of CLT elements, it is preferred that fingers of a length of $L_{FJ} \geq$ 45 mm be introduced (table2). An important role in load bearing falls to the fingers' slenderness, which allows reduction of the pressure strength and enhancement of the joint strength (Colling and Ehlbeck, 1992; Radovic and Rohlfing, 1993; Groom and Leichti, 1994; Smardzewski, 1996).

The growing interest in CLT panels, noted amongst the producers and investors, is justified by a series of economic factors, including primarily the value of the raw material used and the production cost.

The important aspects of the CLT production process are the quality of raw material corresponding to the requirements for the longitudinal planes and proper preparation of a layer set. At this stage of production, the selection of glue systems is the key. Amongst the glues used in the process, there are such as amine glues (fulfilling the requirements of the standard EN 301), melamine-formaldehyde glues (MF), melamine-urea-formaldehyde glues (MUF), and single-component polyurethane glues (1K-PUR) – fulfilling the requirements of the standard EN 15425. Panels are also produced using the Emulsion Polymer Isocyanate adhesives (EPI), which fulfil the requirements of the standard EN 15425 and the European Technical Assessment, which allows their use in load-bearing wooden structures in accordance with the standard EN 16351. Maintaining technological regime during the gluing of wood layers (e.g. maintaining the correct pressure during hydraulic, vacuum or mechanical pressing) provides obtaining correct strength values and stability of the joint. The admissible hydraulic pressure falls within a range of 0.10 ÷ 1.00 N/mm^2; whereas in the case of vacuum presses and the pressure

Table 3 Examples of strength classes of CLT panels (acc. to standard EN 14080)
Tablica 3. Razredi čvrstoće CLT ploča (sukladno standardu EN 14080)

Strength class / *Razred čvrstoće*			
Lamella	GLT	CLT	
		Lamella CV$_{(ft,0,l)}$	
		The coefficient of variation	
		25 % ± 5 %	35 % ± 5 %
T14	GL24h	CL24h	CL28h
T18	GL28h	CL30h	CL34h

CV$_{(ft,0,l)}$ - Accuracy of mechanical grading process with reference to visual grading / *točnost metode mehaničkog klasiranja s obzirom na vizualno ocjenjivanje*

applied using screws, the pressure value should fall within the range of 0.05 ÷ 0.10 N/mm² and 0.01 ÷ 0.20 N/mm², respectively (Kairi, 2008; Brandner and Schickhofer, 2010). The strength of joint between the planes depends on the accuracy of surface machining, pressure of pressing, and adhesive system used.

Studies on the effect of the thickness of materials used for the production of CLT panels are one of the elements of verification of panel strength parameters. Table 4 presents the standard strength indicators for homogenous CLT panel made of 14 mm thick timber of classes C24 and C28 (Jöbstl and Schickhofer, 2007; Brandner and Schickhofer, 2008). The obtained strength parameters in association with thermal insulation indicators, fire resistance (R30 to R90) (Frangi *et al.*, 2009) and ecological aspects, bring CLT products to the forefront of structural materials manufactured from natural raw materials.

While producers and investors show much interest in CLT panels, as mentioned above, the interest of engineers and designers is definitely limited. This stems from the rigorous requirements as to the quality and strength provided by building standards concerning that product. Not long ago, standards concerning the use of CLT were only effective in Germany, Austria, and Switzerland. The development of so-called Eurocode5 (EN-1995-1) made it possible for CLT to

Table 4 Characteristic of the basic mechanical properties of homogenous glued timber CLT
Tablica 4. Obilježja osnovnih mehaničkih svojstava homogenoga lijepljenog drva CLT

Proporties *Svojstva*	**Material T14 /** *Materijal T14*			
	Accuracy of mechanical grading process with reference to visual grading *Točnost metode mehaničkog klasiranja s obzirom na vizualno ocjenjivanje* CV$_{(ft,0,l)}$		**Coefficient of variation** *Koeficijent varijacije*	
			25% ±5%	35% ±5%
			CLT strength class *Razred čvrstoće CLT-a*	
	symbol		CL24h	CL28h
Bending strength / *savojna* čvrstoća	$f_{m.CLT,k}$	N/mm²	24	28
Tensile strength / *vlačna* čvrstoća	$f_{t.0.CLT,net,k}$		16	18
	$f_{t,90,CLT,k}$		0.5	
Compression strength / *tlačna* čvrstoća	$f_{c,0,CLT,net,k}$		24	28
	$f_{c,90,CLT,k}$		2.85	
Shear strength (shear) - in plane *smicajna čvrstoća u ravnini*	$f_{v,CLT,IP,k}$		5.0	
	$f_{T,mode,k}$		2.5	
Shear strength - out of plane *smicajna* čvrstoća *izvan ravnine*	$f_{v,CLT,OP,k}$		3.0	
	$f_{r,CLT,k\ -\ b/t\ \geq 4:1}$		1.25	
	$f_{r,CLT,k\ -\ b/t\ <4:1}$		0.70	
Modulus of elasticity *modul elastičnosti*	$E_{0,CLT,mean}$		11 000	
	$E_{0,CLT,05}$		9 167	
	$E_{90,CLT,mean}$		300	
	$E_{90,CLT,05}$		250	
	$E_{c,90,CLT,mean}$		450	
	$E_{c,90,CLT,05}$		375	
Shear modulus / *modul smicanja*	$G_{CLT,mean}$		650	
	$G_{CLT,05}$		540	
Rolling shear modulus *kotrljajući smični modul*	$G_{r,CLT,mean}$		65	
	$G_{r,CLT,05}$		54	
Density / *gustoća*	$\rho_{CLT,k}$	kg/m³	350	
	$\rho_{CLT,mean}$		385	

enter the building markets of the other European Union member states. Those standards are guidelines for design and use of CLT. Building regulations, currently effective in Europe, determine, inter alia, the requirements as to combustibility of building materials, including primarily wooden elements. The issue of CLT panel combustibility is one of the major issues as regards the design and exploitation of multi-storey buildings. For that reason, the highest CLT buildings were erected outside Europe. In accordance with building requirements, modern structures made of CLT wood are designed in line with guidelines determining the exploitation conditions of a building (EN-1995-1-2). The tests take into consideration the strength conditions, transfer of vibrations, thermal insulation, and fire resistance. CLT is preferred for building purposes because of the favourable ratio of mass to strength, rigidity, and a reduced transverse effect of strength reduction. The adjustment of the American National Standards ANSI/APA PRG 320-2012, which determine the standards of efficiency assessment, production details, and the requirements concerning functional features, in order to assure the required quality, facilitated the use of CLT wood to the full extent in the United States. Thanks to standardization and pro-ecological activities, CLT should also be allowed for in the International Building Code (IBC) (http://www.rethinkwood.com 2013).

One of the basic advantages of CLT panels produced for construction purposes is the low production cost related to low energy-consumption. Therefore, the production process has a positive effect on the reduction of carbon emission to the atmosphere, and thus holding carbon within the cycle. According to comparative studies, the manufacture of 1 tonne of bricks requires four-time-higher energy expenditure than the manufacture of 1 tonne of coniferous timber, the manufacture of 1 tonne of concrete five-time-higher, and the manufacture of a steel or aluminium structure 24-time and 126-time higher, respectively. Wood also demonstrates better insulating properties: five-time higher than concrete and approximately 350-time higher than steel. This means that energy consumption required for heating up and cooling down a wooden building is much lower (Risen, 2014).

4 CONCLUSION
4. ZAKLJUČAK

Speaking about the development of construction based on raw wood material, it can be stated that the use of glued wood (GLT, CLT) indisputably contributed to the broadening of the application of natural raw materials in both single- and multi-storey structures. The use of CLT panels, characterised by highly stable strength parameters, resulted in the introduction of standardization acts organising the scope of CLT panel application. Regulating the production and structural conditions of CLT panels was accompanied by limitations on their use due to wood combustibility. A series of research conducted in order to reduce the susceptibility of wood to combustion suggests that glued wood fulfils the requirements for multi-storey structures. An important asset of constructions based on CLT panels is their strength and stability in the conditions of seismic activity. The scope of applications of wood in the form of CLT panels in construction is affected by the introduction of directives concerning the reduction of CO_2emission into the atmosphere. The success of CLT panels on the world markets derives from factors such as their high receptivity to machining, positive indicator of thermal insulation, and possibilities of modification of their functionality in terms of use and design.

5 REFERENCES
5. LITERATURA

1. Augustin, M.; Blaß, H. J.; Bogensperger, T.; Ebner, H.; Ferk, H.; Fontana, M.; Frangi, A.; Hamm, P.; Jöbstl, R. A.; Moosbrugger, T.; Richter, A.; Schickhofer, G.; Thiel, A. B.; Traetta, G.; Uibel, T.; BSP handbuch, 2010: Holz-Massivbauweise in Brettsperrholz – Nachweise auf Basis des neuen europäischen Normenkonzepts, Verlag der Technischen Universität Graz.
2. Bejder, A. K.; Kirkegaard, P. H.; Wraber, I. K.; Falk, A., 2012: The materiality of novel timber architecture – developing a model for analysing and evaluating materials in architecture. Architectural and Planning Research. Bell, V. B., 2006: Materials for Architectural Design, Laurence King, England.
3. Bejder, A. K.; Kirkegaard, P. H.; Wraber, I. K.; Falk, A., 2011: The materiality of novel timber architecture – based on a case study analysis of Cross-Laminated Timber. ARQ: Architectural Research Quarterly.
4. Bejder, A. K.; Kirkegaard, P. H.; Fisker, A. M., 2010: On the architectural qualities of cross laminated timber. Ed. P. J. S. Cruz, Taylor & Francis Group, London, 119-121. https://doi.org/10.1201/b10428-55
5. Bogensperger, T.; Augustin, M.; Schickhofer, G., 2011: Properties of CLT panels exposed to compression perpendicular to their plane, Proceedings of the 44th meeting of CIB-W18, Alghero, Italy.
6. Bogensperger, T.; Moosbrugger, T.; Silly, G., 2010: Verification of CLT-plates under loads in plane. Proceedings, 11th World Conference on Timber Engineering, WTCE 2010, Trentino, Italy, 20-24.
7. Brandner, R.; Flatscher, G.; Ringhofer, A.; Schickhofer, G.; Thiel, A., 2016: Cross laminated timber (CLT): overview and development. Eur. J. Wood Prod. https://doi.org/10.1007/s00107-015-0999-5
8. Brandner, R.; Schickhofer, G., 2010: Glued laminated timber in bending: thoughts, experiments, models and verification. 11th World Conference on Timber Engineering (WCTE), Riva del Garda, Italy, 11.
9. Brandner, R.; Schickhofer, G., 2008: Glued laminated timber in bending: new aspects concerning modeling. Wood Science and Technology, 42 (5): 401-425. https://doi.org/10.1007/s00226-008-0189-2
10. Brandner, R., 2014: Production and technology of cross laminated timber (CLT): state-of-the-art report, COST Action FP1004, Focus Solid Timber Solutions. European Conference on Cross Laminated Timber, 2nd Edition, Graz, Austria, p. 3-36.
11. Brandner, R.; Schickhofer, G., 2012: SSTC 1.1.2-5 clt panel pressdruck: Untersuchungen betreffend der Definition eines für die Produktion von Brettsperrholzopti-

malen Pressdruckes. Research Report, Institute of Timber Engineering and Wood Technology. Graz University of Technology, Competence Centre holz.bauforschungsgmbh, p. 76.

12. Ceccotti, A., 2010: Cross Laminated Timber Introduction to Seismic Performance, Trees and Timber Institute IVALSA-CNR National Research Council, Italy. Available at www.bcwood.com/resources/cross-laminated-timber-symposium-presentations.
13. Colling, F., 1990: Tragfähigkeit von Biegeträgern aus Brettschichtholz in Abhängigkeit von den festigkeitsrelevanten Einflussgrößen, Dissertation. Universität Fridericiana Karlsruhe, p. 205.
14. Colling, F.; Ehlbeck, J.,1992: Tragfähigkeit von Keilzinkenverbindungen im Holzleimbau, Bauen mit Holz, 94 (7): 586-593.
15. Cziesielski, M., 1974: Timber roof structures, multi-layer composite structure of boards &beams.
16. Espinoza, O.; Trujillo, V. R.; Laguarda; Mallo, M. F.; Buehlmann, U., 2015: Cross-laminated timber. BioResources, 11 (1): 281-295. https://doi.org/10.15376/biores.11.1.281-295
17. Evans, L., 2013: Cross Laminated Timber: Taking wood buildings to the next level. http://www.rethinkwood.com/sites/default/files/Cross-Laminated-Timber-CEU.pdf 2013.
18. Falk, A.; Buelo, P.V., 2011: Form Exploration of Folded Plate Timber Structures based on Performance Criteria, Taller, Longer, Lighter: meeting growing demand with limited resources: IABSE-IASS 2011. Hemming Group Ltd., London, p. 467.
19. Falk, A., 2010: Wood as a Sustainable Building Material. In: Wood Hand-book, Chapter 01. General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory: 1-1, 1-6.
20. Falk, A., 2011: Cross-laminated timber plate tensegrity and folded roofs. Wood for Good - innovation in timber design and research. Ed. Larsen, Olga Popovic and Lee, Daniel Sang-Hoon, The Royal Danish Academy of Fine Arts, 91-107.
21. Follesa, M. et al., 2010: Mechanical in-plane joints between cross laminated timber panels, WCTE World Conference on Timber Engineering.
22. Fragiacomo, M., 2014: Seismic behavior of cross-laminated timber buildings: numerical modeling and design provisions. COST Action FP1004, Focus Solid Timber Solutions. European Conference on Cross Laminated Timber, 2nd Edition. Graz, Austria, p. 3-36.
23. Frampton, K.; Cava, J., 1995: Studies in tectonic culture: the poetics of construction in nineteenth and twentieth century architecture. Graham Foundation for Advanced Studies in the Fine Arts, Chicago.
24. Frangi, A.; Fontana, M.; Hugi, E.; Jübstl, R., 2009: Experimental analysis of cross-laminated timber panels in fire. Fire Safety Journal, 44 (8): 1078-1087. https://doi.org/10.1016/j.firesaf.2009.07.007
25. Gold, S.; Rubik, F., 2008: Consumer attitudes towards timber as a construction material and towards timber frame houses – selected findings of a representative survey among the German population. Journal of Cleaner Production, 17: 303-309. https://doi.org/10.1016/j.jclepro.2008.07.001
26. Groom, L. H.; Leichti, R. J., 1994: Effect of adhesive stiffness and thickness on stress distributions in structural finger joints. Journal of Adhesion, 44: 69-83. https://doi.org/10.1080/00218469408026617
27. ***http://www.rethinkwood.com 2013.
28. Jöbstl, R. A.; Schickhofer, G., 2007: Comparative examination of creep of GLT and CLT slabs in bending. Proceedings of the 40th meeting of CIB-W18. Bled, Slovenia, 2007.
29. Kairi, M., 2002: Glued / Screwed Joints / Screw Glued Wooden Structures. Chapter 4.4. In: Johansson, C. J., Pizzi, T. and Leemput, M. V. (eds.). COST Action E13 “Wood Adhesion and Glued Products”, Working Group 2: Glued Wood Products: State of the Art Report.
30. Li, Y., 2015: Duration-of-load and size effects on the rolling shear strength of cross laminated timber. Ph.D. Thesis, Department of Wood Science, University of British Columbia.
31. Li, Y.; Lam, F., 2016: Low cycle fatigue tests and damage accumulation models on the rolling shear strength of cross-laminated timber. J. Wood Sciences, 62: 251-262. https://doi.org/10.1007/s10086-016-1547-6
32. Massivträ: Håndbogen, 2006: Trätek, Industrikonsortiet Massivträ, SE.
33. Muszyński, L., 2015: The CLT talk. 2015 Small Log Conference, Forest Business Network, Coeur d’Alene, ID.
34. Pavlyukovskiy, A., 2012: Using of Cross Laminated Timber in Russia. Bachelor’s Thesis.
35. Pei, S.; Popovski, M.; van de Lindt, J. W., 2012: Seismic design of a multi-story cross laminated timber building based on component level testing. World Conference on Timber Engineering, Auckland. ttp://www.timberdesign.org.nz/files/00279%20Shiling%20Pei.pdf 2012.
36. Pei, S.; van de Lindt, J. W.; Pryor, S. E.; Shimizu, H.; Isoda, H., 2010: Seismic testing of a full-scale six-story light-frame wood building: NEES Wood Capstone test. NEES Wood Report NW-04.
37. Pilagin, A. V., 2006: Design of bases and foundations of buildings and structures, Moscow: ASV.
38. Plackner, H., 2015: Brettsperrholzwlichst global. Holzkurier, p. 12 -13.
39. Popovski, M., 2010: Seismic Performance of CLT Construction. FP Innovations. Available at http://www.cecobois.com/index.php?option=com_content&view=article&id=315&Itemid=199.
40. Radovic, B.; Rohlfing, H., 1993: Über die Festigkeit von Keilzinkenverbindungen mit unterschiedlichem Verschwächungsgrad. Bauen mit Holz, 3: 196-201.
41. Risen, C., 2014: The World’s Most Advanced Building Material Is. Wood. Popular Science 2014. http://www.popsci.com/article/technology/worlds-most-advanced-building-material-wood-0?dom=PSC&loc=recent&lnk=5&con=the-worlds-most-advanced-building-material-is-wood.
42. Roos, A.; Woxblom, L.; Mc Cluskey, D., 2010: The Influence of Architects and Structural Engineers on Timber in Construction – Perceptions and Roles. Silva Fennica, 44 (5): 871-884. https://doi.org/10.14214/sf.126
43. Schickhofer, G., 1994: Starrer und nachgiebiger Verbundbeigeschichteten, flächenhaften Holzstrukturen, Dissertation. Institute of Steel, Timber and Shell Structures, Graz University of Technology.
44. Schickhofer, G., 2010: Cross Laminated Timber (CLT) in Europe – from Conception to Implementation, presentation. University of British Columbia, Department of Wood Science, Vancouver, Canada.
45. Smardzewski, J., 1996: Distribution of stresses in finger joints. Wood Science and Technology, 30: 477-489. https://doi.org/10.1007/BF00244442
46. Sturzenbecher, R.; Hofstetter, K.; Eberhardsteiner, J., 2010: Structural design of Cross Laminated Timber (CLT) by advanced plate theories. Composites Science and Technology, 70 (9): 1368-1379. https://doi.org/10.1016/j.compscitech.2010.04.016

47. Thiel, A., 2014: ULS and SLS Design of CLT and its implementation in the CLT designer, COST Action FP1004, Focus Solid Timber Solutions. European Conference on Cross Laminated Timber, 2nd Edition. Graz, Austria, p. 77-102.
48. Van de Lindt, J. W.; Rammer, D.; Popovski, M.; Line, P.; Pei, S.; Pryor, S. E., 2013: Lateral Design of Cross-Laminated Timber. Chapter 4 in CLT Handbook: Cross-Laminated Timber, U.S. Ed. Special Publication-SP-529E. FP Innovations.
49. Vdovin, V. M.; Karpov, V. N., 1999: Structures made from plastic and timber. Moscow, ASV.
50. Wathén, R., 2006: Studies on fiber strength and its effect on paper properties, Dissertation. KLC communications, No. 11. University of Technology, Helsinki, Finland.
51. Werner, F.; Richter, K., 2007: Wooden Building Products in Comparative LCA. https://doi.org/10.1065/lca2007.04.317
52. Zumbrunnen, P.; Fovargue, J., 2012: Mid-rise CLT buildings, the UK's experience and potential for Australia and New Zealand. Proceedings, 12th World Conference on Timber Engineering, WTCE 2012. Auckland, New Zealand, p. 91-98.
53. *** 2001: EN 387:2001-10, Glued laminated timber – Large finger joints – Performance requirements and minimum production requirements.
54. *** 2005: EN 14081-1:2005-11, Timber structures – Strength graded structural timber with rectangular cross section - Part 1: General requirements.
55. *** 2006: EN 301:2006-06, Adhesives, phenolic and aminoplastic, for load-bearing timber structures – Classification and performance requirements.
56. *** 2009: EN 338:2009-10, Structural timber – Strength classes.
57. *** 2010: EN 384:2010-04, Structural timber – Determination of characteristic values of mechanical properties and density.
58. *** 2010: Introduction to cross-laminated timber, FP Innovations, Pointe-Claire, Canada.
59. *** 2011: EN 16351:2011-11, Timber structures – Cross laminated timber – Requirements.
60. *** 2012: American National Standard/APA, PRG 320 Standard for Performance-Rated Cross-Laminated Timber, 2012.
61. *** 2012: DIN 4074-1:2012-06, Strength grading of wood – Part 1: Coniferous sawn timber.
62. *** 2012: EN 14080:2012-02, Timber structures – Glued laminated timber and glued solid timber – Requirements.
63. *** 2012: EN 16351:2012-01, Holzbauwerke – Brettsperrholz – Anforderungen.
64. *** EN 15425:2017, Adhesives. One component polyurethane (PUR) for load-bearing timber structures. Classification and performance requirements.
65. *** EN 1995-1-1. Eurocod 5. Design of timber structures – Part 1-1: General – Common rules and rules for buildings.
66. *** EN 1995-1-2 -Eurocode 5. Design of timber structures. General. Structural fire design
67. *** Z-9.1-209, Dreischichtplatten aus Nadelholz der Fa. Schwörer Haus KG, Schwörer Haus KG, DeutschesInstitut für Bautechnik (DIBt), 2011, valid until 1. 9. 2016
68. *** Z-9.1-482: KLH-Kreuzlagenholz, KLH Massivholz GmbH, Deutsches Institut für Bautechnik (DIBt), 2010, valid until 17. 11. 2015.
69. *** Z-9.1-501, MERK Dickholz ® (MDH), Finnforest Merk GmbH, Deutsches Institut für Bautechnik (DIBt), 2009, valid until 31.01.2014.
70. *** Z-9.1-534 "Binderholz Brettsperrholz BBS", Binderholz Bausysteme GmbH, DeutschesInstitut für Bautechnik (DIBt), 2012, valid until 6. 12. 2014.
71. *** Z-9.1-555, LIGNOTREND-Elemente, LIGNOTREND AG, Deutsches Institut für Bautechnik (DIBt), 2008, valid until 25. 6. 2013.
72. *** Z-9.1-559: CLT – Cross Laminated Timber, Stora Enso Wood Products Oy Ltd, Deutsches Institut für Bautechnik (DIBt), 2012, valid until 13. 1. 2017.
73. *** Z-9.1-574, THOMA-Holz 100 System, Ing. Erwin Thoma Holz GmbH, Deutsches Institut für Bautechnik (DIBt), 2008, valid until 30. 6. 2013.
74. *** Z-9.1-640, Massivholzplatten – Layer-plus-static, Rettenmeier Holding AG, Deutsches Institut für Bautechnik (DIBt), 2006, valid until 30. 9. 2011.
75. *** Z-9.1-721: Gegenstand: ED-BSP (Brettsperrholz) aus Fichte, Kiefer oder Douglasie, 2013.

Corresponding address:

MAREK WIERUSZEWSKI, Ph.D.

Poznan University of Life Sciences
Faculty of Wood Technology
Department of Wood-Based Materials
Wojska Polskiego Street 38/42
60-637 Poznan, POLAND
e-mail:mwierusz@up.poznan.pl