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American tulipwood (*Liriodendron tulipifera* L.) as an innovative material in CLT technology

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Abstract: *American tulipwood (Liriodendron tulipifera L.) as an innovative material in CLT technology*. CLT (cross laminated timber, X-Lam) is one type of engineered wood products. The first idea of CLT was presented in the seventies of the last century. It is manufactured with timber boards placed side by side commonly with 3, 5 and 7 layers glued at 90 degrees to adjacent layer. The CLT production technology was developed for softwood. The main species in CLT production is Norway spruce (*Picea abies* L.) and less often White fir (*Abies alba* Mill.). Hardwood is also used more and more for production of CLT, most often, the wood of Silver birch *(Betula pendula* Roth.), Ash (*Fraxinus excelsior* L.), poplars (*Populus spp*.), Locust tree (*Robinia pseudoacacia* L.). This paper describes the suitability of cheap tulipwood (*Liriodendron tulipifera* L.) as a raw material for the production of CLT. Examples of the use of this type of panels in construction are also presented. The tulipwood has similar physical characteristics to softwood, for which CLT production technologies were previously developed. This makes it possible to use the technology previously for softwood CLT was developed. In addition, the tulipwood is characterized by aesthetic visual quality (wood surface similar to marble). Thanks to this, CLT boards to make exposed surfaces can be used.

Keywords: tulipwood, *:* cross laminated timber, engineered wood, hardwood

INTRODUCTION

Wood has been a valuable construction material for thousands of years. Due to the high price of good quality wood and intensive development of new technologies, wood - and wood-like materials are increasingly used (e.g. plywood, OSB – oriented strand board, LSL – laminated strand lumber, LVL – laminated veneer lumber, PSL – parallel strand lumber). These materials have got wood-like mechanical parameters and often similar visual impression. In recent years, the technology of the so-called engineered wood has been developing particularly intensively. Engineered wood (also known as „man-made wood" or composite wood) is conducted from multiple layers ort part of wood connected using heat, glue and pressure. Cross laminated timber (CLT), also called X- lam, is one of the subcategories of engineering wood. The first idea of CLT was presented in the seventies of the last century (Cziesieski, 1974). Over the following years, the concept of cross-gluing wood was intensively developer (Brandner, 2013). Development of CLT technology have been realised primarily in Austria and Germany, where in the early 90's the CLT as an innovative material was presented. Over the next years, the CLT production technology was constantly improved and the application possibilities expanded. CLT is a wood panel product made from gluing together layers of solid-sawn lumber. The number of wooden layers is unpaired. Each layer consists of closely spaced and parallel boards; adjacent layers are perpendicular to each other. CLT is a multi-dimensional material with many advantages, e.g. high dimensional stability, high load capacity in two planes(Günther, 2019). Nowadays, CLT technology is increasingly used in the construction of residential buildings and also buildings intended for offices, schools and kindergartens. The physical and mechanical properties of this product depend on many factors, e.g. number of layers and their thickness, the width and thickness of the boards in the layer, class of lumber, species of wood. The species of wood used for the production of CLT is not only an important factor determining the physical and mechanical parameters of these boards, but also has a significant impact on production costs. This paper describes the suitability of cheap tulip wood (*Liriodendron tulipifera* L.) as a raw material for the production of CLT. Examples of the use of this type of panels in construction are also presented.

CLT MAIN CHARACTERISTICS

CLT (cross laminated timber, X-Lam) is one type of enginered wood products. It is manufactured with timber boards placed side by side commonly with 3, 5 and 7 layers glued at 90 degrees to adjacent layer according to Standard EN 16351 (Fig. 1) . Structural timber for the production of CLT can be selected according to Standard EN 338: 2016. The big advantage of CLT is the possibility of using out-of-grade timber; e,g. CLT made from very low stiffness timber can still achieve spans 80% of the equivalent CLT produced from in-grade timber (Gagnon and Popowski, 2011). Panel thicknesses is usually between 60mm and 500mm; in sizes typically 3,5m wide and up to 16m long. Adhesives are often used for timber connection (polyurethane being most common, melamine urea-formaldehyde or phenolresorcinol-formaldehyde less often) (Crespell and Gagnon, 2010). Sometimes other fastening systems are used, such as steel, aluminium or wooden – nails, screws or dowels and timber-to-timber interlocking systems (Smith, 2011)

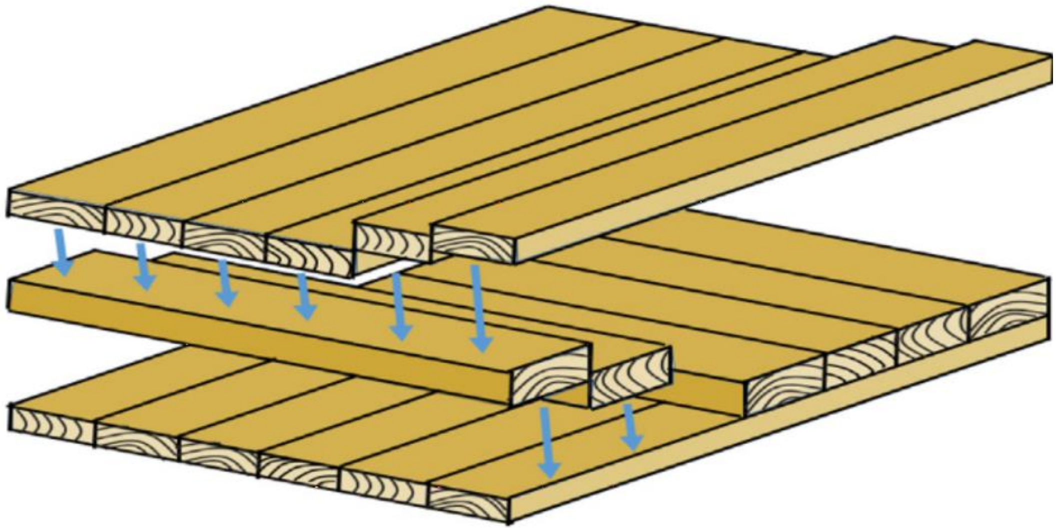

Figure 1. Cross laminated timber (CLT) (after Cherry et al., 2019)

This way arranged CLT structure provides great load-bearing capacity and structural stiffness in both directions (horizontally- through the layers planes/laminations and verticaly – on the surface plane/laminations of the panel element) (Causevic and Rustempasic, 2020). Due to the fact that CLT is used as a construction material in buildings (also multi-storey) (Ringhofer and Schickhofer, 2014; Kotwica and Krzosek 2018; Kotarski and Przepiórka, 2020, such its parameters as fire resistance and soundproofing are very important. Wood is very predictable in fire - the outer layer of cross-laminated wood panel will initially ignite, and then build a charred layer of insulation that provides 30, 60 or more minutes of fire resistance, depending on the number and size of the panel. In the case of CLT, the fire resistance depends not only on wood type, but also on the type of adhesive used (e.g. glue) and the size of intralamination spaces. Compared to other wood-like materials, CLT also has a high resistance to fire. Due to the little free space inside CLT, this material slowly char and fire does not spread. (Crespell and Gagnon, 2010; Stauder, 2013). An important parameter of CLT as a building material is soundproofing. CLT unfortunately has low soundproofing (especially for low frequency sounds). Covering the CLT with an additional material, e.g. drywall, eliminates this disadvantage (Ferk, 2013). Next very important parameters of building materials is thermal conductivity coefficient. In the case of CLT, this parameter is practically the same as in the case of solid wood; it is therefore dependents on the base material. Many studies have show, that there is a linear relation between wood density and thermal conductivity – increase of wood density = increase thermal conductivity coefficient = decrease isolation properties (Mac Lean, 1941, Mason et al., 2016, Cavus et al., 2019). CLT has, like other wood products, relatively good thermal insulating characteristics. CLT heat conductivity, (lambda value, expressed in W/m°C) is comparable with lightweight concrete and there is substantially lower than for concrete and steel. CLT has a comparatively high specific heat capacity (thermal inertia). Usually it is around 1300 J/kg°C, which is higher than concrete (about 880J/kg°C). Although CLT is quite a new material, its production is growing rapidly. In recent years, the CLT board industry has been developing very intensively in Europe but also in the USA, Canada and China ((Muszyński et al., 2020). In 2016, Europe produced about 680tys m^3 CLT and forecast production for 2020 was 1.78 million m^3 (an increase of about 1 million m^3**) (**Günther, 2019). Manufacturers of CLT in Europe produce them based on the European Technical Approvals - ETA, e.g. Binderholz produces CLT based on ETA-06/0009 issued on June 2, 2017 by the German Institute of Building Technology (Deutsches Instytut für Bautechnik) in Berlin, while Hasslacher - based on ETA-12/0281 issued on November 9, 2020 by HOLZFORSCHUNG Austria in Vienna.

WOOD SPECIES USED IN THE CLT TECHNOLOGY

The CLT production technology was developed for softwood (in France in the mid-eighties of the last century – first CLT patent). The main species is Norway spruce (*Picea abies* L.) and less often White fir (*Abies alba* Mill.). Furthermore, softwood such as European larch (*Larix decidua* Mill.), Scots pine (*Pinus sylvestris* L.), Swiss stone pine (*Pinus cembra* L.), Douglas fir (*Pseudotsuga menziesii* Mirb.), Maritime pine (*Pinus pinaster* Alton) are used. Hardwood is also used more and more for the production of CLT. Most often, the wood of Silver birch *(Betula pendula* Roth), Ash (Fraxinus excelsior), poplars (*Populus spp*.), Locust tree (*Robinia pseudoacacia* L.). Thanks to use of hard wood (e.g. ash wood, locust wood), the CLT panel can retain certain mechanical parameters with a reduced thickness. Often, hard hardwood is used only for the outer layers CLT; inner CLT layers are made of cheaper and less durable birch or poplar wood. This significantly reduces the cost of CLT production while maintaining aesthetic values and mechanical parameters (Stauder, 2013).

The ideal type of wood for the production of CLT seems to be low-density (like softwood) and high-strength (like hardwood). Low density wood is important not only because of ease wood processing and transport. This feature is also very important due to the use of methods in CLT technology, that for softwood were developed (e.g. using self-drilling screws for softwood without drilling holes beforehand). With more and more exposure of CLT surfaces the material aesthetics is also important. The above-mentioned requirements seem to be met by tulipwood.

CHARACTERISTICS OF TULIPWOOD

Tulip trees, belonging to the *Magnoliaceae* family, are represented by two species American tulip tree (known as tulipwood, tulip poplar, whitewood, fiddle tree, or yellow-poplar) and Chinese tulip tree (*Lirodendron chinense* Hemsl.) (commonly known as the Chinese tulip poplar, Chinese tulip tree or Chinese whitewood). American tulip tree grows in the forests of North America (not in the extreme northerly and south-easterly parts), Australia and Brazil. It has also been planted in Europe for over 300 years as a park and ornamental tree. In its natural habitat, it is one of the tallest deciduous trees (it grows even above 60m). Natural habitats of Chinese tulip trees are in China and Vietnam, where these trees grow up to 40m in height. The American tulip tree is the most common representative of tulip trees in the world .

Tulipwood is characterized wide growth ring boundaries distinct. Heartwood is yellow to green to brown (darkening to olive-brown), mostly without streaks (rarely with dark stripes). Sapwood colour distinct from heartwood colour and is creamy white (for this reason, tulipwood is called “whitewood”) (Fig. 2). Tulipwood is susceptible for fungal diseases and insects (Beck and Della-Bianca, 1981).

Figure 2. Wood surface of American tulip tree (*Liriodendron tulipifera* L.) (*Fot. T. Kłosińska*)

Tulipwood is diffuse-porous. Vessels in multiples, commonly short (2–3 vessels) radial rows and in clusters (predominantly in radial groups). Average tangential vessel diameter 40–70–120 µm. Perforation plates scalariform, with 3–5–10 bars. Helical thickenings absent. Tyloses in vessels present, thinwalled. Rays multiseriate, also if only few, (1–)2–3(–4) cells wide (uniseriates rare). Rays composed of two or more cell types. Heterocellular rays square and upright cells restricted to marginal rows. Number of marginal rows of upright or square cells 1 ((Richter and Dallwitz, 2000). The microscopic structure of the American tulip wood is shown in Figure 3.

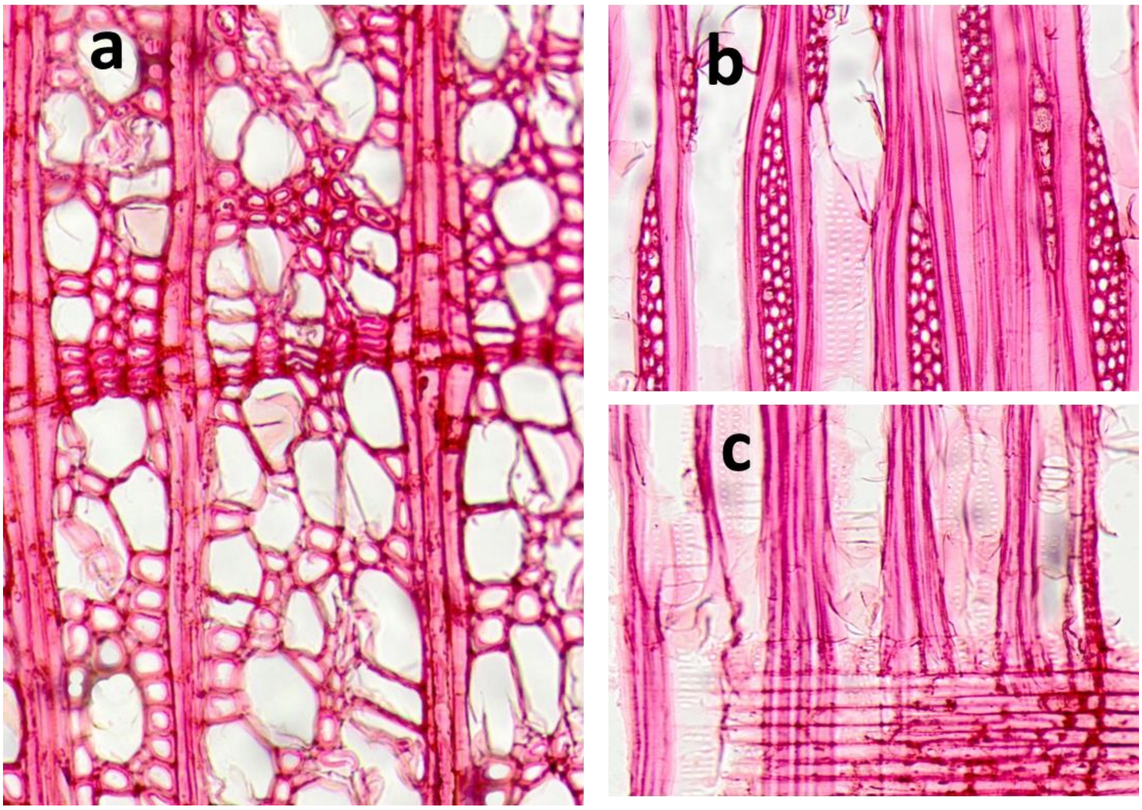

Figure 3. The microscopic structure of the American tulip wood (*Liriodendron tulipifera* L.): a – transverse section, b – tangential section, c – radial section; (*Fot. T. Kłosińska*)

Despite low density, tulipwood shows surprisingly good physical and mechanical parameters. Table 1 shows selected physical and mechanical parameters of tulipwood and spruce wood, which is often used in CLT production. The literature data presented in table 1 indicate that parameters such as density, modulus of rapture (MOR), modulus of elasticity (MOE) are similar for tulipwood and spruce wood. As a result, previously developed for softwood CLT technology for the tulipwood CLT production can be used. Gluability is an important parameter of the wood used in the production of CLT. Given tulipwood's lower porosity compared to similar density softwood (Plötze and Niemz, 2011) its gluability is lower too. Covering the glued surface with an appropriate primer solution helps to solve this problem and and opens the tulipwood timber for the adhesive.

Tabe 1. Selected physical and mechanical properties of American tulip wood ((*Liriodendron tulipifera* L.)

	Selected physico-mechanical parameters of American tulipwood	
	American tulip wood (*Liriodendron tulipifera* L.)	Norway spruce (*Picea abies* L.)
Owen-dry wood density	440 kg/m^3 (Sława-Neyman and Owczarzak, 2020)	457kg/m^3 (range: 300-640kg/m^3) (Sława-Neyman and Owczarzak, 2020)
Density (MC = 15%)	560kg/m^3 (Sława-Neyman and Owczarzak, 2020)	497kg/m^3 (range: 340-680kg/m^3) (Sława-Neyman and Owczarzak, 2020)
Round wood density	710kg/m^3 (Sława-Neyman and Owczarzak, 2020)	783kg/m^3 (range: 700-850kg/m^3) (Sława-Neyman and Owczarzak, 2020)
Modulus of rapture (MOR) (MC=15%)	80MPa (Sława-Neyman and Owczarzak, 2020) 83,4 (range: 49,4-108,6) (Uzcategui et al., 2020) 81,35 (Newlin and Wilson, 2017) 69,63 (Kretschmann, 2010)	87,7 (range:49-135 MPa) (Sława-Neyman and Owczarzak, 2020)
Modulus of elasticity (MOE) (MC=15%)	9611 MPa ((range: 7067-12259 MPa) (Uzcategui et al., 2020) 11100MPa ((Newlin and Wilson, 2017) 10893MPa (Kretschmann, 2010)	13233 (range: 7300-21400MPa) (Sława-Neyman and Owczarzak, 2020)

ADVANTAGES AND DISADVANTAGES OF TULIPWOOD AS A MATERIAL FOR CLT

Advantages:

- Wood relatively cheap and readily available in the market.
- Aesthetic visual quality of wood (wood surface similar to marble). Thanks to this, CLT boards make exposed surfaces can to be used.
- Low density. This makes it easy to process and transport. It also allows the use of technology previously developed for softwood. Its wood may be compared in texture, strength, and softness to pine wood, especially to white pine. It has a high strength to weight ratio so it is ideal for use as a structural material.
- Fast growing. The American tulip tree is one of the fastest growing trees. Under favorable environmental conditions, it grows up to 5O cm per year (Mazik, 2019). A large tree attaining a height of 37m or more, and a diameter of 2m or more (https://www.trada.co.uk/wood-species/tulipwood/).
- A versatile timber that is easy to machine, plane, turn, glue and bore. Dries easily with minimal degrade. Very good dimensional stability and little tendency to split

when nailed. Takes and holds paint, enamel and stain exceptionally well (https://www.internationaltimber.com/product/tulipwood/).

- The tests showed the particular strength and stiffness of the tulip wood in the process of perpendicular shearing (Lawrence, 2020). Because CLT is a cross-laminated timber, perpendicular shear has a relatively large effect on the stiffness. This is especially important for a floor-based CLT (determines the vibration range of the floor panel).

Disadvantages:

- Low gluability
- It is susceptible wood for fungal diseases and insects.
- It cannot withstand to the hot and dry climates.
- It can easily be damaged in winter season

Due to the above-mentioned disadvantages, the wood of the American tulip tree exposed to climatic and biological factors must be well protected.

THE USE OF CLT FROM TULIPWOOD IN WOOD CONSTRUCTION

Idea with CLT using American tulipwood at the end of 2012 was created. This idea was the result of research conducted at AHEC (American Hardwood Export Council). Together with Arup, AHEC has been experimenting with CLT made from fast-grown tulipwood for the past decade. First construction from cross-laminated tulipwood is Endless Stair (cluster of interlocking stairs), has designed by Alex de Rijke of dRMM. for London Design Festival 2013 (commission for the American Hardwood Export Council) De Rijke describes this structure, which is several storeys high (187 steps and 7.7m high), as a ´three-dimensional exercise in composition (architect was inspired by Escher's graphics). The interlocking wooden staircases are configured to create a maze of walkways and a viewpoints towards the city's skyline across the Thames. It was planned that the installation would be placed next to St. Paul's Cathedral in London. Finally, it placed next to the Tate Modern Galeria and it provide visitors with views of both the Tate Modern and the river Thames (https://www.americanhardwood.org/pl/examples/our-projects/the-endless-stair).

In the above-mentioned architectural studio, the design of the world's first tulipwood CLT building was prepared. The authors of this project were Alex de Rijke and Jasmin Sohi. Based on their design, the Maggie’s Centre in Oldham was built in 2017 (https://www.archdaily.com/874795/maggies-oldham-drmm). This hospital was first engineered hardwood building (from tulipwood CLT). Almost the entire hospital building (260m^2) is made of tulipwood. Clad in corrugated, thermally treated tulipwood ((in order to improve the resistance of tulip wood to atmospheric and biological factors), and with the same wood worked into cross laminated timber to create the main load-bearing structure, the building is as lovely to look at as it is to use.

A very interesting construction, created with the use of tulipwood CLT, was “The smile”. This project was created by Alison Brooks has collaborated with The American Hardwood Export Council, Arup Company and The London Design Festival. This structure was shown at the Chelsea College of Art Rootstein Hopkins Parade Ground (London) from 17 September until 12 October 2016. “The smile” (136m^2) was built for visitors for the duration of the festival. The construction was a 3.5 m high, 4.5 m wide and 34 m long rectangular curved tube, made from the largest CLT plats available, which are 4.5 x 20 m. The structure was a huge arc, forming two cantilevers from a single point in the centre. The structure was designed to resist approximately 10 tonnes of wind loading. It was screwed to a large wooden box that was filled with 20 tonnes of steel weights to prevent if from tipping over (https://materialdistrict.com/article/smile-london-made-clt/) .

Another unusual installation from CLT, shown at the London festival in 2018 is "Multi Ply" This installation was created in cooperation with the British architectural studio Waugh Thistleton Architects, the American Hardwood Industry Trade Association (AHEC) and the ARUP Company. The structure was shown in the Sackler Courtyard at the Victoria and Albert Museum in London. The design "Multi Ply" (a play on the words multiply and plywood) was based on a modular principle in which a cubic space is duplicated and piled up to form a nine-meter structure. It consists of labyrinth-like elements. A total of 17 modules were installed, consisting of 102 60mm- and 100mm-thick, 2.60m-long tulipwood CLT panels. The panels were connected to each other like a three-dimensional puzzles, simply with finger joints and screws. Here, for the first time ever, thermally modified wood (TMT) was used as a protective layer for the CLT modules (https://www.world-architects.com/it/architecture-news/products/multiply). The aim of the project was to provoke a discussion on ecology in the construction industry and a new approach to city building.

As can be seen from the examples cited, tulipwood can be a substitute for softwood in CLT production. It is quite cheap and easily accessible. This wood is most often harvested from North America forests, which are quickly renewing themselves. Not without significance is the fact that the tulipwood has similar physical characteristics to softwood, for which CLT production technologies were previously developed. The use of tulipwood CLT means that large-scale wooden buildings can be built without the use of concrete or steel. Like other CLT boards, tulipwood CLT is ideal for prefabrication and rapid assembly, reducing construction times by around 30%. These properties, together with its impressive appearance, make tulipwood a perfect pioneer for innovative wood construction.

SUMMARY

CLT (cross laminated timber, X-Lam) belongs to the engineered wood group and is a fairly new product (the idea was born in the seventies of the last century). It is manufactured with timber boards placed side by side commonly with 3, 5 and 7 layers glued at 90 degrees to adjacent layer. Sometimes other fastening systems are used, such as steel, aluminium or wooden – nails, screws or dowels and timber-to-timber interlocking systems CLT boards are most often made of softwood (e.g. Norway spruce and less often White fir). Hardwood is also used more and more for the production of CLT (e.g. silver birch, ash, poplars, locust tree). Hardwood normally have strength comparable or greater than that of softwood of the same density thus can be good raw material for CLT production. The previously developed CLT technology from softwood to produce CLT from similar density hardwood can be used. Such wood is, for example, tulipwood. In the case of tulipwood wood, parameters such as

density, modulus of rapture (MOR), modulus of elasticity (MOE) are similar as for spruce wood, which is often used for CLT production. The big advantage of tulipwood is aesthetic visual quality (wood surface similar to marble). Thanks to this, CLT boards make exposed surfaces can to be used. Tulipwood as a material for CLT boards also has disadvantages, e.g. susceptible for fungal diseases and insects. Until now, tulipwood CLT boards only in a few building structures was used, mainly for design festivals. It seems, that tulipwood CLT will be often used in construction in the future, especially where tulipwood is easily available and cheap (e.g. Canada, USA).

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Streszczenie: *Drewno tulipanowca amerykańskiego ((Liriodendron tulipifera L.) jako innowacyjny materiał w technologii CLT.* CLT (drewno klejone krzyżowo, X-Lam) to jeden z rodzajów drewna inżynieryjnego. Pomysł produkcji tego typu płyt powstał w latach 70-tych ubiegłego wieku a w połowie lat osiemdziesiątych została opracowana technologia produkcji CLT z drewna iglastego. Są to wieloformatowe, konstrukcyjne płyty z drewna klejonego krzyżowo wyprodukowane w 100% z masywnego drewna litego. Płyty CLT są produkowane z tarcicy układanej w warstwy, przy czym poszczególne warstwy są przestawione względem siebie o kąt 90°i łączone najczęściej klejem. Głównym gatunkiem w technologii CLT jest świerk pospolity (*Picea abies* L.), rzadziej jodła biała (*Abies alba* Mill.). Coraz częściej do produkcji CLT wykorzystuje się również drewno liściaste, najczęściej drewno brzozy brodawkowatej (*Betula pendula* Roth), jesionu (*Fraxinus excelsior* L.), topoli (*Populus spp*.), Robinii akacjowej (*Robinia pseudoacacia* L.). W artykule opisano przydatność taniego drewna tulipanowca amerykańskiego (*Liriodendron tulipifera* L.) jako surowca do produkcji CLT. Przedstawiono również przykłady wykorzystania tego typu płyt w budownictwie. Drewno tulipanowca ma podobne właściwości fizyczne do drewna iglastego, dla którego wcześniej opracowano technologie produkcji CLT. Dzięki temu możliwe jest wykorzystanie technologii opracowanej dla miękkiego drewna iglastego. Dodatkowo, drewno tulipanowca charakteryzuje się estetycznym wyglądem (powierzchnia drewna przypominająca marmur). Dzięki temu płyty CLT z drewna tulipanowca amerykańskiego można wykorzystać do wykonania odsłoniętych powierzchni.

Słowa kluczowe: drewno tulipanowca, drewno klejone krzyżowo, drewno inżynieryjne, drewno liściaste

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