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Timber - Material of the Future - Examples of Small Wooden Architectural Structures

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Abstract. The aim of this article is to present various types of wood-based products, classified as engineered timber, while specifying the implications of their structural properties for their forms. Timber is used as a construction material due to its fire resistance, good structural characteristics and insulating properties. The advent of new technologies of wood processing and wood-based materials production has converted timber into a high-tech material, thus encouraging the architects to consider it ever more often in their projects. As wooden technologies overcome constraints, timber begins to compete with steel and concrete. The design characteristics of new wood-based products allow wooden structures to be higher, have larger spans, and more diverse forms than ever. Wood-based materials include materials made of solid wood, veneers, strand, and wood which, due to its inferior quality, would otherwise be unfit for constructions. Elements and layers of these products are glued using different kinds of strong and water-resistant adhesives. The article presents the history of development of new wood technologies, discussing increasingly popular wood-based materials such as glued laminated timber, cross-laminated timber, or structural composite lumber. The paper analyses their technical and fire-resistance properties, and points to ecological aspect, as factors contributing to the growing popularity of these materials. Finally, the timber's characteristics are contrasted with those of steel and concrete. The article lists examples of wooden objects representing the so-called small architecture structures from across Europe. They illustrate the potential, the uniqueness and the versatility that wood-based materials offer for constructors and architects. All these features form sufficient grounds for stating that timber truly is a construction material of the 21st century.

1. Introduction

For the last few years both traditional wooden constructions, which use solid timber, as well as modern technologies taking advantage of wood-based materials, have been developing dynamically. Today, engineered wood enables to create elements of all shapes and sizes, thus becoming the perfect material for designers. Having high compressive and tensile strength, it allows wooden structures to be higher than ever before, reaching more than six storeys. Today, such buildings are constructed all around the world, and currently the highest one is The University of British Columbia in Vancouver, Canada, with its eighteen storeys and is 53 metres of height.

Processed wood, successively overcoming its limitations, is now able to compete with steel and reinforced concrete, in many cases surpasses them in terms of insulation or fire resistance parameters.

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2. Engineered wood

The development of the technology of Engineered Wood Products (EWP) has its origins in the 19th century. Its history begins with the glued laminated timber patented by Otto Hetzer in 1906. The technology consisted of bonding two or more lamels with a water-proofing glue, which was stronger than the timber itself. The elements could be long, straight or have any desired curve, while their size could reach up to 40 meters. In addition, they were cheaper than steel or reinforced concrete structures. These properties rekindled interest in wooden constructions, which was declining after the industrial revolution. In 1910, the first building to use Hetzer's construction was erected. It was a single storey shed for German Railways, designed by Peter Beherns for the World's Fair in Brussels. Its span length reached 43 meters. Later, in 1911, the copula of the building of the University of Zurich was made using same material. In that period glued laminated wood was often utilised as it did not require any protection against corrosion. In later period Hetzer's system gained particular popularity in Sweden and Norway [1,2,3,18].

Engineered wood products are a group of materials elaborated by gluing various wood-based elements such as boards, veneers and strands. These include plywood, oriented strand board (OSB) as well as the construction materials presented below. Their characteristics, which in some cases exceed steel and concrete, render them an excellent construction material. [9]

2.1. Crucial Characteristics of Engineered Wood

- higher strength in terms of deformation, torsion and a lower shrinkage in comparison to traditional timber construction methods, due to the composite nature and drying the material to 12%. [8]
- high strength compared to other construction materials. Japan Housing and Wood Technology Center (HOWTEC), based in Japan, carried out comparative tests of wood, concrete and steel in regard to their tensile, compressive, and flexural strengths. The research focused on the ratio between the weight and the materials' parameters. As presented in Table 1, the study concluded that wood had substantially higher strength than the remaining materials.
- economy of the solutions. High load capacity and low mass reduces the consumption of material. Prefabrication is contributing to the economy too. [14] Precision of elaboration limits the time required for fitting the elements together, thus speeding the assembly process, and eliminates breaks imposed by the technological process, as in the case of concrete structures. Additionally, less personnel are required, allowing high structures to be erected in just several weeks. To provide an example: London's ten storeys Murray Grove was built in less than nine weeks by just four workers.
- flexibility in terms of shaping arches and curvatures. [8]
- ecology at all life cycles of the element. Wood is a renewable raw material and forest economy is aimed at efficient supply of lumber. The energy demand for timber construction is 50% lower than in the case of steel and ca. 40% lower than that of concrete. It is healthier in use and naturally regulates humidity. It is also a biodegradable material. [14, Tab.1]
- fire resistance. Proper cross-sectional shaping of the elements allows a resistance of 120 minutes. Also, it is possible to calculate the rate of carbonisation of wood, offering more predictability than in the case of steel. [11]
- weight benefitting the economy. Lower transportation costs, smaller foundations. Wood is fourteen times lighter than steel and four times lighter than concrete. [Tab.1]
- naturalness contributing to high comfort of use.

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Table 1. Comparison of Materials' Properties

	Density [kg/m^3][b]	Tensile strength [MPa][a]	Flexural strength [MPa][a]	Compressive strength [MPa][a]	Heat transfer [W/(m·K)][b]	Total Energy Use [GJx10^3]	CO2 Emissions [kgx10^3]
Timber	550	220	274,6	93	0,16	3,8	73
Steel	7850	49,9	17,85	43,6	58	7,35	105
Concrete	2200	0,98	0,69	9,8	1,3	5,5	132

a. http://structure.kes.ne.jp/kes-system/safety.html, Experiments conducted by the Japan Housing and Wood Technology Center, HOWTEC, documented in the book `Timber and Japanese houses', Comparison of the material strengths of timber, concrete and steel (testing the same weight of each material)
b.PN-EN ISO 6946
c.Total Energy Use and CO2 Emissions Resulting from Construction of Three-Story Office Buildings of Concrete, Wood, and Steel - Forintek Canada Corporation/Canadian Wood Council. 1997. Comparing the Environmental Effects of Building Systems - A Comparison of Wood, Steel, and Concrete Construction in 3-Story Office Buildings. Wood the Renewable Resource Series, Case Study Number 4.

2.2. Types of Engineered Wood
Engineered wood technology is being continually developed. New methods, parameters, and types of glued laminated timber are studied. The possibilities of shaping glued wood are limited only by transportation and assembly constraints. Different glued woods use different components. They may be manufactured with boards, veneers or strands. Also, the arrangement of fibres in the layers plays an important role. The fibres may be unidirectional or have a cross-wise arrangement. The components used for panels' production and the arrangement of fibres within them define their use and strength. Engineered wood often plays complementary roles in constructions.

2.2.1. Glued Laminated Timber
Glued laminated timber (GLULAM) is the oldest type of engineered wood. It is elaborated with the use of boards glued with melamine-formaldehyde or phenol-resorcinol-formaldehyde adhesives. In GLULAM the fibres of all layers of an element are oriented lengthwise. It is used primarily as straight columns, beams, and arches, [12].

2.2.2. Cross Laminated Timber
The cross laminated timber (CLT) is a very robust material with a wide range of applications. The production technology was developed in Switzerland in the 1990s. Its popularity is constantly growing and today CLT is widely used in Europe, the United States and Australia. CLT, the most common of all engineered woods, boasts high strength, large size and the ease of combining with other types of laminated timber.

It is a composite material comprising solid wood boards. It is produced by gluing subsequent layers together with their fibres oriented orthogonally relative to the neighbouring ones. Such arrangement gives the material high strength and stiffness while reducing shrinkage. Odd number of layers is being put together until achieving the desired thickness (even number of layers is rarely used). The layers are made of solid wood and can be composed of smaller elements glued together. The size of the elements is limited by transportation and assembly capacities. In Europe, the main material for CLT production is spruce. Cross laminated timber, due to its high strength, is used for erecting high structures. Often, these buildings have a hybrid construction and combine timber with concrete. CLT has a wide range of applications. Owing to its parameters it can be used either as bearing elements or for partition purposes. Cross laminated timber elements are also used for ceilings and staircases. Although made of wood, when given a proper cross-sectional profile, CLT can guarantee up to 120 minutes of fire resistance. Also, due to its mass, CLT offers good thermal and acoustic insulation properties. The prefabrication technology

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allows to deliver ready-to-use elements to the construction site, equipped with service openings, doorways, and window openings. This reduces the amount of waste generated during the construction works in comparison to concrete structures. [9, 13, 14, 15].

2.2.3. Structural composite lumber

One of the sub-groups of EWPs is structural composite timber. It comprises such material as laminated veneer lumber (LVL), parallel strand lumber (PSL), laminated strand lumber (LSL), and oriented strand lumber (OSL). Moisture-resistant adhesives are used for gluing.

Laminated Veneer Lumber (LVL) is produced with a 2.5-4.8 mm thick veneer. It uses various types of timber, depending on its availability. It can either be produced from conifers, such as spruce or pine, but also from deciduous species, such as poplar, birch, or eucalyptus. In LVL, the fibres are arranged in a parallel manner. To secure desired characteristics of the material, ultrasound scanner is used for veneer selection. Veneer sheets are glued with melamine-formaldehyde and phenol-formaldehyde adhesives. The sheets are bound by pressure and temperature. Such prefabrication makes LVL a highly homogeneous material. It is a strong material that offer favourable strength-to-weight ratio. Although Laminated Veneer Lumber is not a new material, only recently has the array of its applications become wider. Initially, in the 1950s, it was mainly used in the aviation industry. Today it has a much wider range of applications; it serves as a material for construction elements, such as columns, joists, and trusses. LVL panels can also be used as walls, floors, or roof elements. It is a strong material, flexible in terms of size and thickness of elements. Large LVL elements also offer benefit from reduced number of assembly connections. [4,5,6,16,17]

Parallel Strand Lumber (PSL, also known as Parallam) is made of long strands from different kinds of timber, mostly pine, poplar, and Douglas fir. The strands are laid in parallel formation length-wise to the element. PSL elements, usually 3 mm thick, 20 mm wide, and 0.6 to 3 m long, are manufactured by cutting veneers. Once the veneer is dried, it is cut into strands and faulty elements are removed. Then, the strands are laid in the desired formation and bonded with an adhesive, most commonly phenol-resorcinol-formaldehyde glues. Finally, the element is compressed and the glue is cured with microwaves. The length of the element, due to the use of through-fed presses, is limited by the capacities of the production facility and the means of transportation. The production often utilises waste from laminated veneer lumber or plywood production. PSL is predominantly used as columns and beams, reaching up to 30 meters, as well as in frame constructions. [6, 8, 10]

Laminated Strand Lumber (Intrallam or LSL) is also produced from strands. It is the newest laminated wood from the structural composite timber group. The production technology resembles the OSB, but the final product is thicker. It uses poplar, aspen, or lime tree strands, ca. 0.8 mm thick, 20-50 mm wide, and 300 mm long. The strands are the by-product of timber fibres lengthwise machining. They are bonded under pressure with polyurethane adhesives and steam. The strands are laid in a parallel or crosswise formation, and then cut to the desired size. The orientation of the strands affects the strength of the material. Those manufactured with parallel strands are weaker and thus can be used as beams, rafters, or columns, while the crosswise oriented strands can be used as walls, ceilings, and floors. LSL elements have minimum shrinkage and distortion. Nonetheless, it is a weaker material than LVL. [6, 7, 19, 20]

Oriented Strand Lumber (OSL) is a material that is produced in exactly the same way as the LSL. It differs however in the size of strands, which are smaller than in Laminated Strand Lumber. [6]

3. Examples of Small Wooden Architectural Structures

Processed wood serves as a building material for various objects, whose size and the span continues to increase. The last decade has brought, in particular, a growing interest in high-rise structures. Constructing the world’s highest wooden building has become a sui generis race.

Nonetheless, timber is also used in small architectural forms. Processed wood is becoming an increasingly popular material in small architecture designed for public spaces. Thanks to its properties, it can be formed practically without any constraints. The following part presents a selection of small-scale objects designed using glued timber. They exemplify small architectural forms which, thanks to the technology, can be located in spaces where they fulfil their spatial, societal and exhibition-related functions.

3.1. Winter Cabin on Mount Kanin

The project titled Winter Cabin is located on the Italian-Slovenian boarder, on Mount Kanin. It was carried out by OFIS architects, a Slovenian company, and completed in 2016. Winter Cabin is a type of a compact 2.4 metres wide, 4.9 metres long mountain shelter. Its modest interior of 9.7 sq. meters can host up to 9 persons. It comprises three platforms for resting and a small living space. The main structure is made of cross-laminated timber in order to provide the necessary strength. As the materials were delivered on site by a helicopter, their weight was also an important aspect. The structure is thermally insulated with rock wool aluminium panels. The interior displays plain timber. Winter Cabin is set on an uneven ground, anchored with steel ropes on the verge of the slope, so as to reduce its impact on the rocks. The structure's exposure to extreme weather, strong winds, and rapid temperature changes have been taken into consideration in its design, and the use of CLT is meant to secure resistance to these factors. [21,23]

Winter Cabin may be considered a social project. It was funded with subsidies while the entirety of the works was carried out by volunteers, [22]. The shelter creates a single, small meeting space for strangers from different backgrounds, representing different walks of life. The co-presence in such a peculiar and confined area offers a high probability of interactions among the temporary dwellers, which may result in establishing relations and creating a social bond. Additionally, from a sociological standpoint, the perception of this space is heavily influenced by the condition, in which the previous users leave the space for those who are to come after them.

The pavilion on Mount Kanin is accessible only for climbers. Thus, its users are an exclusive group. While, the roof pitch is inspired by local architecture, the structure itself is a thoroughly modern design. Its form attracts not only with its compact size, but also with the way its sides are "open" to the surrounding landscape, as the site has a double exposure. On the one hand the climbers can enjoy being in a unique spot in the mountains, which offers a spectacular view, while on the other hand they have an opportunity to interact with a unique architectural form.

3.2. Periscope Tower

Periscope Tower is located on the coast of Kyrösjärvi in Finland (Figure 1). Kyrösjärvi is an artificial lake. Apart from regulating water level, its construction created attractive recreational and housing areas. Periscope Tower was designed by OOPEAA of Finland for a housing fair. The project's aim was to create an overlook by the lake. The structure's purpose was to add attractiveness to the site and draw attention of local inhabitants, [24].

Periscope Tower's construction is made of wood. The inner core is made of cross-laminated timber, while the outer part is supported by a solid wood frame. The Tower consists of four prefabricated elements: three of them constitute the core, and the fourth forms the roof. [25]

The core of the structure is the tube of the periscope. The mirrors mounted on top and at the bottom allow disabled and elderly persons to see the panorama without the need to walk up the stairs. Those who wish to climb the tower can either reach the top observation platform, equipped with seats, or use other platforms located at the lower levels of the structure. They offer view from every side of the tower, [24].

Figure 1. Photo of Periscope Tower built on shore lake in Finland, [33]

Also, the Periscope Tower serves as a stimulus of local community's activities. Its presence contributes to attractiveness of the area around Kyrösjärvi, encouraging local inhabitants to visit the place more often. If several persons congregate at a given spot, it offers possibilities for establishing relations between them. Adding to social value, the students from a local SEDU vocational school were asked to participate in the construction of the Tower. It allowed them to put their theoretical knowledge to practice and offered an opportunity to experience real-life implementation of a construction project, [25]. Periscope Tower is an interesting example of integrating a small architectural form into the landscape. Its function transcends merely being a local attraction, and points to the natural values of its surroundings. Additionally, the use of mirrors while adapting the building to the needs of persons with reduced mobility merges creativity with the broadly interpreted idea of accessibility.

3.3. Endless Stair

Figure 2. Photo of Endless Stair in fornt of Tate Modern, [34]

Endless Stair is an installation art created for the 2013 London Design Festival. It was designed by architects from dRMM and engineers from Arup. It was originally located in the vicinity of Tate Modern

(Figure 2). Apart from being a sculpture and an overlook, Endless Stair carried out social functions. It consisted of fifteen flights of stairs, [26].
The construction was made of cross-laminated timber. In this case, instead of using softwood, the creators used liriodendron hardwood. The Stair served as an experiment carried out by the American Hardwood Export Council, a hardwood producer. CLT was selected due to its desirable weight-to-strength ratio. Wood's remarkable parameters allowed to create an intriguing form, which demonstrated the capabilities of cross-laminated timber. The designer, Alex de Rijke, referred to CLT as the material of the 21st century, the new concrete, [27].
The creators chose the form of stairs, due to their interesting sculptural aspect. The structure, comprising 183 stairs could be freely rearranged. At night, the installation was illuminated, highlighting its plasticity and visual attractiveness. The flights of stairs were chosen because of their social aspect. The project's author, professor Alex de Rijke, stressed that the people who walk must meet at their crossing points, [27].

3.4. The Smile
The Smile was designed as an installation art for the 2014 London Design Festival. The sculpture was designed by architect Alison Brook. As in the case of Endless Stair, the cross-laminated timber was used for the construction. Also, again, softwood was substituted with liriodendron tulipifera hardwood – a light and strong material. The Smile was the first project to utilise industrial-size CLT hardwood panels that allow erecting entire buildings, [29].

Figure 3. Curve shape was connected with a ground in a narrow, central section [35]

Figure 4. The Smile after dark was lighted **[**36]

The simple block – a curved cuboid – bent resembled a smile (Figure 3). The installation was 34 meters long, 3 meters high, and 4.5 meters wide. However, the fundamental feature was the demonstration of the capabilities of the CLT technology. Andrew Lawrence, the director of Arup, the designer of the construction of The Smile, stated that the potential of the cross-laminated timber was used in to the maximum. The installation had a single fulcrum and was anchored with a twenty-tonne ballast. Walls of The Smile were fitted with apertures allowing sunlight into the interior, thus offering a constantly changing illumination. The location of the perforations had been carefully calculated so as to coincide with the areas of least tension within the structure. Both ends of the structure were left open and equipped with balconies with a view over the city. Much attention was dedicated to illumination (Figure 4). Artificial lighting was meticulously elaborated to allow a kind of play of lights. The Smile was an interesting example, both artistically and technologically, with all the measures applied thoroughly planned beforehand. Created with state-of-the-art materials, it demonstrated the possibilities for contemporary constructors and architects, [28,30,31].

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3.5. P3

P3 is an installation art created during a workshop organised by students' association at the Technical University of Łódź in 2013 (Figure 5). On the one hand, it was conceived as an answer to the needs of the students from the campus, on the other hand, it was an opportunity to acquire knowledge on parametric design. The pavilion was built entirely of plywood. A CNC milling machine was used to cut 570 panels, comprising a total of 3500 elements (Figure 6). Once assembled, the construction was 9 by 9 meters, and 3.5 meters high. P3 serves as an excellent example of the possibilities that timber offers in terms of prefabrication. Its great advantage is the easiness and precision of processing when using professional tools.

Figure 5. P3 was installed in fornt of University as a place of students meetings [37]

Figure 6. Pavillon was made of playwood panels [38]

The P3 pavilion was a major success. It quickly became an integral element of the landscape. Apart from successfully carrying out its utilitarian functions, P3 generates highly positive emotions and is a spot that generates different interpersonal relations. As the organisers put it themselves: "P3 is a magnet and a generator. It attracts curious passers-by. It provokes various reactions, some just look at it from a short distance, others walk inside and touch it." The pavilion has also become a space for culture. From the very beginning it was planned as a meeting point and an exhibition site. It also served as place for artistic expression, being used as a screen for video-mapping. [32]

4. Conclusions

Although timber has been used in constructions for centuries, wooden technologies constantly continue their development. Timber today, adjusted to new requirements and with outstanding technical properties, successfully competes and often replaces steel and concrete. In the age of high awareness regarding health and environmental issues, engineered wood – combining excellent design parameters with its life cycle of virtually minimum environmental impact – simply seems to be the better choice.

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