DESIGNING A ZERO-WASTE MASS-TIMBER HIGH-RISE LOAD-BEARING STRUCTURE

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ABSTRACT

An increasing amount of people is living in urban areas and this is expected to increase till the end of this century. Sustainable solutions are required to prevent resource depletion and to reduce carbon emissions. Mass-timber can be used to extend existing buildings due to its lightweight properties, preventing demolition and waste, and to densify the city. Timber is a renewable resource with a negative carbon footprint in contrast to traditional building materials. This paper examines the possibilities for designing zero-waste mass-timber high-rise extensions using case studies of existing projects, literature study and a study into mass-timber products. Because of the lightweight nature of mass-timber the structure should be suitably designed for stability to prevent overturning of the structure. It is also shown that structural modifications can enable larger load bearing capacities in existing structures for extensions. All wood mass-timber products can be used as a zero-waste building material in combination with metals, although in the future bio-resins can enable the use of more timber products. In combination with demountable connections a zero-waste design can be achieved.

KEYWORDS: *mass-timber, zero-waste, high-rise, densification, extension*

I. INTRODUCTION

The world is facing a global housing problem. The world population is growing and an increasing larger percentage of the population is living in cities (The Open University, 2016). 55% of the world's population lived in an urban area in 2018 according to the United Nations and this is expected to rise to 68% in 2050 (United Nations, 2018). In combination with the expected world population of over 9 billion, this could mean that an additional 2.5 billion people will move to urban areas in the coming years. The world population is expected to even further increase towards the end of the century with a total of 11 billion people in 2100 (United Nations, 2017). 90% of the urban population increase will probably take place in the continents of Asia and Africa. The building industry is responsible for around 36% of energy consumption worldwide, of which 30% in use and 6% in construction industry, and for 39% of the world CO2 emissions in 2015, of which 28% is of buildings in use and 11% of the construction industry (United Nations Environment, 2017).

The environmental awareness in the building industry is increasing and the buildings are increasingly optimized for the use-phase, resulting in more energy efficient buildings. The contribution percentage of the construction industry and demolition itself however, will become larger because of this trend. Moreover, when buildings no longer meet the functional requirements, they will be demolished or renovated, generating demolition waste. Demolition waste is a heterogeneous collection of materials that cannot be economically reused or recycled. Think of, for example, shattered coated glass and reinforced concrete. The heap of materials is difficult to separate back into its original materials such as steel, glass, cement, water. It is therefore often dumped on a landfill or incinerated (de Lange & van Houten, 2016). New materials are mined for new buildings and this will eventually lead to a depletion of resources. It is forecasted that the global volume of construction and demolition debris is expected to increase from 1.3 billion tons of waste every year to 2.2 billion tons in 2025, accounting for half of the solid waste production worldwide (Redling, 2018). The amount of waste generated from demolition is significantly higher than from the construction phase. This demolition waste can be prevented by designing for the end of life of a building using zero-waste principles, according to de Lange and van Houten (2016).

The material choice of a building has a large impact on designing for zero-waste, as well as on the embodied energy and carbon emissions. Mass-timber, defined as solid panels of wood engineered for strength through lamination of different layers, is a building material that, when the timber is harvested properly, has a net negative carbon emission (Green, 2017). This means that a building constructed using mass-timber can store carbon and in effect reduce total greenhouse emissions. Moreover, timber is a re-grow able material that can be produced indefinitely. Mass-timber has also been shown to be suitable to construct mid-rise and high-rise buildings, such as TREET in Bergen, Norway and Mjøstårnet in Brumenddal, Norway. Making it a suitable candidate to densify urban areas using high-rise buildings.

The lightweight properties of mass-timber, in general 4 times lighter than concrete, makes it ideal for extending existing buildings. In the master thesis Optimal Vertical Extension by Papageorgiou (2016) the extensions of existing buildings upwards are shown to be a viable addition to the tools to densify existing cities. Extending existing buildings can be a useful strategy to solve the scarcity of living space in urban areas. In the master thesis Tall Timber Extension by Gonzalez (2017) it was shown that if mass-timber is used in vertical extensions it has three advantages: it is a solution for crowded cities, it is a sustainable building materials and a sustainable method to use the existing building stock and preventing demolition.

This paper is a research into designing load bearing structures using zero-waste principles and mass-timber for extending existing structures. This can be an additional solution to densify our cities sustainably for the future. The following research question will be answered:

How to design a mass-timber high-rise structure as an extension to an existing building using zero-waste principles?

The research will limit itself to the load bearing structure of the building. Steel and concrete are almost always used for the load bearing structure of high rises and these materials contribute most to the large carbon footprint and to the generation of demolition waste. The load bearing structure also contains the largest volume of material in a building.

II. Methods

This chapter will discuss the methodology and methods used in this research. First the main research question will be broken down in sub-questions. The methodology and method in which these are researched are also discussed. In the second part the zero-waste requirements will be summarized. These will be used in the research to determine whether a material or method is zero-waste.

2.1. Research questions & methodology

In order to answer the research question, it has been divided into three sub-questions The research results in this paper are split accordingly to these questions:

1. *What building methods are suitable for high-rise mass-timber structures?*
2. *How can a structure be built on an existing structure?*
3. *What are the properties of mass-timber and the different products available and how do these relate to the required zero-waste principles?*

The first sub part of the research is about determining the suitable building methods and structural principles for building tall with mass-timber. The information is acquired via literature study, examining the state of the art in building tall with mass-timber, and using five case-studies of finished high-rise mass-timber structures. In each case study the structural methods and details are analyzed using photographs, drawings and schemes.

The second sub part is about how existing buildings can be extended vertically. On the basis of literature study and four case studies, various methods and techniques will be discussed. Each case study is examined for structural methods employed and are analyzed using construction photographs, drawings and schemes. The findings will be judged using the zero-waste requirements in order to determine which can be used in a zero-waste design.

The third part determines the properties of mass-timber in a structural design, covering some general material properties and the design for a safe structure in fire. Information about the different mass-timber products in the building industry will be gathered from manufacturers, suppliers and literature study. Each mass-timber product will be examined for mechanical properties, typical use, manufacturing and applications. The products will then be evaluated using the zero-waste requirements.

2.2 Zero-waste requirements

The goal of the research is to determine the methods for a zero-waste design. The methods and materials that are examined are evaluated using the zero-waste requirements as presented in *A zero-waste approach in the design of buildings* by de Lange and van Houten (2016). This part shortly summarizes the requirements.

There are primary and secondary zero-waste demands. The primary demands define what zero-waste is and is stated in Table 1. The materials should be re-useable and recyclable/regrowable, as governed by the first two demands. The third demand suggests that a building, component or material should be kept useful as long as possible before recycling or biodegrading. The secondary zero-waste demands are supports for the design to make actual zero-waste disassembly as attractive as possible at the end of life, these are presented in database 1 (Appendix pp. 2-4)

Table 1: Zero-waste primary demands (de Lange & van Houten, 2016, p. 22)

Zero waste primary demands		
Number	**Demand**	**Description**
1	0 kg waste during all (de)construction phases of the building	Waste is defined as materials or as a mix of materials that have no future use. It is no longer wanted, has no value. The materials are either landfilled or incinerated. This demand states that the building may not produce any waste during construction, renovation and demolition. This demand sets the main goal of zero-waste. It is important that for this goal the complete life of the building and the materials used are taken into account.
2	Every material should remain in its respective material cycle	This second demand hints towards the solution of designing a zero-waste building. Bio-based materials remain in the biosphere and metals, minerals and such should remain in the technosphere. The life of a material cannot be linear. Waste generation is prevented in this way.
3	Reuse of materials should be made possible in such a way that invested/embodied energy is maintained as much as possible, or can easily be increased.	This demand is based on the Delft Ladder. If a material or component is kept high in the ladder, it will result in a more easily reusable element. Although the primary goal is not focused on embodied energy, it can be an indicator for zero-waste. When invested energy is quickly wasted, this means the component is moving towards waste.

In a zero-waste design this means that only materials that can be endlessly reused or recycled should be used. The materials may also not be dangerous or polluting. The total amount of different materials should also be kept to a minimum. The connections in a zero-waste design should always be demountable or be made of the same material. This ensures that each component can eventually be disassembled back into singular materials which can be reused or recycled. Disassembly should also be made as attractive as possible at the end of life. The total amount of components in the design should therefore also be kept to a minimum. A building or component should be designed according to the hierarchy of lifespans of different components. This prevents unnecessary actions or unreachable components when maintenance, replacements or disassembly is required.

III. RESULTS

This chapter discusses the results of the research. This is divided into three sections. The first discusses the mass-timber high-rise structures, the second discusses how existing structures can be extended vertically and the third discusses the properties of the material timber and the different mass-timber products available and their possible use in a zero-waste structure.

3.1. Mass-timber high-rise structures

For the load bearing structure of a tall building two forces determine the final structure: gravity and horizontal loads. The taller a building becomes, the more material will rest on the structure, and thus a larger gravity load. Timber (around 450 kg/m^3 for softwood) has a far lower density than reinforced concrete (around 2400 kg/m^3). It also has a higher strength to weight ratio compared to concrete (Figure 1), which means that a building of comparable height in concrete or will be heavier than a mass-timber structure. This means that the total load on the foundation will be lower. This property of mass-timber is also the biggest problem. When dealing with horizontal loads, caused mainly by wind and some by eccentricity, the building is inclined to tip over. A mass-timber high-rise structure should therefore not only be designed for the stresses wind loading causes to the structure but also for resisting the moment trying to turn over the entire building. Several structural methods can be used to deal with this problem. For high-rises in general the following methods can be distinguished (Nijsse, 2012, p. 71): rigid portals, structural core, structural core with outrigger, tube structure, megastructure.

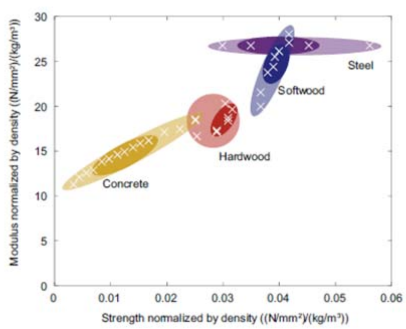

Figure 1 Compression strength and modulus of construction materials normalized by density (Ramage et al., 2017, p. 348).

The portal structure is made stable by resisting the horizontal forces in the connections and subsequently by absorbing the induced moments in the columns and the foundation. This is therefore not a suitable method for mass-timber, as it will not only require stronger beams and columns, but also stronger connections. A possibility is to use an existing structure to provide the stability, as is demonstrated by the Tamedia Office building (Appendix p. 6).

A different approach in mass-timber structures is the use of a cellular structure. This structural principle has been demonstrated in the Forté Living by Andrew Nieland, and Murray Grove (Appendix p.7) and Dalston Works by Waugh Thistleton Architects. Mass-timber panels are used to form a stable structure by arranging them in a cellular fashion. The panels form stable cells which in turn form a stable building. These are also dimensioned for robustness to prevent progressive collapse. Floors are over dimensioned for example to cantilever or span double length or walls are dimensioned for double their height.

The structural core is a proven principle and is already being applied in mass-timber structures. These cores are however still made out of concrete, because of the higher strength and the concrete forms a monolithic structure. An example is the Brock Common Tallwood House (Appendix p.9). It is possible to create a structural core using mass-timber panels from large elements, but the challenge will be in connecting the panels together to form a whole rigid core structure. Mass-timber columns and beams, often made from glulam and LVL, are used to form the frame around the core.

In addition to a structural core, outriggers can be used to reduce to overall moment in the structure. An outrigger is a rigid frame which connects the structural core to the perimeter columns. This creates in effect a larger distance for the bending moment induced by the wind to act upon, which will result in smaller forces in the core and columns. Outriggers are ideally placed at the top of the structure, but can also be used multiple times throughout the total height. This principle is also demonstrated in the TREET building (Appendix p.8).

The tube structure makes in essence a core which encompasses the entire building (Nijsse, 2012, p. 88). The columns and beams of the outer perimeter are connected rigidly and absorb the moment. This is however a weak system and not suitable for a mass-timber structure, as is also discussed with the portal structure. The tube structure can be combined with the core structure (tube in tube structure), but this will underperform compared to the (multiple) outrigger structure. An advantage of a tube structure is that the horizontal loads will always be spread on two planes (the outer perimeters parallel to the horizontal load) and has a high torsion resistance.

The megastructure is a smart tube structure which uses diagonals to create triangles in combination with the perimeter columns, which are in essence the best option to provide stability. It is basically a large vertical truss. Because the outer perimeter is used of the building, the forces are kept to a minimum in the foundation. This system can also be used in combination with a structural core. The Mjøstårnet building, currently the tallest mass-timber high-rise in the world, uses the megastructure method (Appendix p.10), but does not utilize the core for structural purposes.

Mass-timber can also be used in combination with other materiasl to form a hybrid structure. In existing mass-timber mid-rise structures, mass-timber is often used in combination with concrete to provide additional mass on the floors and for a structural core (Gonzalez, 2017, pp. 16-17). Concrete is however not a zero-waste material. Steel or other metals can be used as these are fully recyclable (de Lange & van Houten, 2016, p. 157). It should be noted that metals do perform worse in higher temperatures in the case of fire and need to be protected. This can be done by encapsulating the metal, either in timber or with fully recyclable plasterboards. Mass-timber can be designed for fire safety, as discussed in chapter 3.3.

It is also not uncommon to combine mass-timber structures with steel. It can for instance be used for bracing or in combination with timber beams to form trusses. In the Limnologen building steel rods are anchored in the concrete foundation and extend all the way to the top floor and press the CLT panels together, counteracting the tension forces induced by the horizontal forces (Serrana, 2009). This system has to be re-tightened periodically due to relaxation in the steel and creep deformations in the timber.

Steel is also used often to create connections between mass-timber elements. It is ideal to connect vertical elements together, separate from beams or floors. Because timber is an anisotropic material, the grains will get crushed in compression perpendicular to the grains. Platform type structures should therefore be avoided. Steel can be used as an intermediary material to transfer the forces. This is also shown by the case studies, where steel plates are used in combination with dowels or bolts to connect mass-timber elements together (Appendix pp.8, 10) or steel nodes are used to transfer vertical loads directly from column to column (Appendix p.9). Next to these properties, using steel for connections is ideal for designing for disassembly. Bolted connections or dowel connections can be disassembled and reused, without damaging the mass-timber elements.

Lastly the foundation, and also often the ground floor, is made out of reinforced concrete in all mass-timber structures. This is done because when timber is used in the soil, or any humid environment, it will rot and decay. It is also used to create larger spans or act as a transfer floor. It is common to have a different function on the ground floor which requires larger unobstructed space than the floors above. This poses a problem with zero-waste requirements, and is proven to be difficult to solve with zero-waste methods (de Lange & van Houten, 2016, pp. 230-285).

A solution could be to use an existing structure as a foundation for the mass-timber building or to reuse a foundation, as will be discussed in the next chapter. Recoverable steel piles, such as screwed piles could also be used, but this still leaves a problem for the ground floor. A possible solution would be to lift the ground floor from the ground using steel, ensuring a dry timber structure.

3.2. Extending existing structures

Extending existing structures is often a complex task, the building may have deteriorated over time or may not be strong enough to support additional loads. When extending a structure, the gravity load will increase and, more importantly, the moment caused by the wind will increase exponentially with the height next to the increased wind speeds at greater heights. The most important parameters for a design to extend an existing building is the strength of the structure, with regard to the increased vertical forces and horizontal forces, and the load bearing capacity of the foundation. Maria Papageorgiou (2016) defines three different scenarios in her thesis *Optimal Vertical Extension* as shown in Figure 2, with each scenario increasingly more costly but also able to achieve a higher structure.

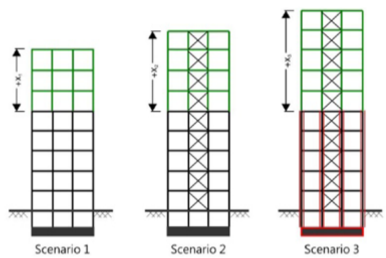

Figure 2 Schematic representation of three different scenarios: 1. Extension without strengthening the existing structure; 2. Extension with slight modification or strengthening of the existing structure; 3. Extensive strengthening of the existing structure (Papageorgiou, 2016, p. 104).

It is likely that an existing reinforced concrete frame structure has an over capacity (Relker, 2013, p. 89). Strength calculations done in the past often have a larger redundancy than used in current calculation methods. A recalculation of the structure and foundation can show hidden strength of the existing structure. A foundation can also have become stronger when piles are used, because due to soil compaction the strength of the soil can increase. A concrete structure also gradually becomes stronger over time due to the continuing hydration of concrete. The existing building could also have been designed for a higher live load, such as in the case of an industrial building (Appendix p.14) or a warehouse being transformed (Appendix p.12) into a residential or office function.

In order to achieve greater heights, the structure will have to be modified. A common strategy is to introduce a stronger stability system, which can potentially unlock hidden strengths in a structure. This could be new bracings, a new structural core, an outrigger or winged core structure. The Karel Doorman (Appendix p.15) and the Westerlaan (Appendix p.13) case studies are good examples of such interventions. This strategy is best used in a situation where the existing structure relies on rigid portals for stability, as the beams and columns will no longer need to resist the moments induced by wind loads. This capacity can then be used to support the additional structure. The foundation can also be slightly altered by for example spreading the loads of the building more evenly or more efficient, as shown in the Westerlaan case study (Appendix p.13). A more simple solution is to remove (parts of) the existing building and replacing it with a lighter structure. Columns, beams and floors can also support more loads if their span or effective length is shortened.

The height of an extension can be further increased if the existing structure is also strengthened using structural interventions (Johansson & Thyman, 2013; Papageorgiou, 2016, pp. 39-48). Jacketing can be used to increase the strength of columns, beams floors and walls. An external material, such as steel strips or fiber reinforced plastic, is applied to the surface and can greatly increase the capacity of the element. Another method is to simply increase the section of the element with new material in order for the element to cope with larger stresses. It should be noted that this method also increases the dead load of the total building. Strengthening an existing foundation can be challenging as it is often difficult to reach with large machinery. New steel screw foundation piles can be inserted to increase the loading capacity of the foundation (Johansson & Thyman, 2013, pp. 70-73). Grouting or soil injection can also be an option.

3.3. Material properties

Presumably the biggest problem with using timber as a structural material is fire. Mass-timber is in contrast to steel and concrete a combustible material. Mass-timber however behaves different in fire than light wood frame structures often associated with timber construction due to their solid nature (Green, 2017). Instead of burning, mass-timber will char and form a protective layer. This charring behaves predictable and structures can be calculated for a fire safe design by exploiting this behavior and adding a sacrificial layer. The fire resistance rating is calculated based on the minimal required structural thickness and the remaining sacrificial thickness available for charring. Moreover, in comparison to steel, mass-timber will not lose structural strength in higher temperatures. The big advantage in designing for zero-waste is thus the ability to design for fire safety without the need for additional materials or coatings.

Conventional methods for creating a fire safe design can also be used. A sprinkler system is advisable and is used in every mass-timber building to reduce the risk of the building burning down (Appendix database 2 pp.5-10). Combined with a detection system to ensure emergency services are alerted timely, the chance of structural failure can be greatly reduced. Encapsulation is also an option to protect structural members from fire. This method however is not always zero-waste. Care should be taken to select fully recyclable materials, such as gypsum boards, to encapsulate the mass-timber elements. It should also be fixed in a demountable method, in order to recover the elements and material and the end of life of the building.

Several mass-timber and timber panel products have been researched and can be found in the appendix database 4 (Appendix pp. 16-26). A graphic summary of the production methods of the products is shown in Figure 3. A distinction can be made between products made from sawn lumber, products made from veneers and products made from strands. The stranding and peeling methods use most of the logs, while sawing leaves around 50% of wasted material. This could however subsequently be used as strands or recycled into other products such as chip boards, wood bonded panels or wood fiber insulation (Scalet, 2015). Many of the products use glue as a method for lamination, with dowel-laminated- and nail-laminated-timber being the exception.

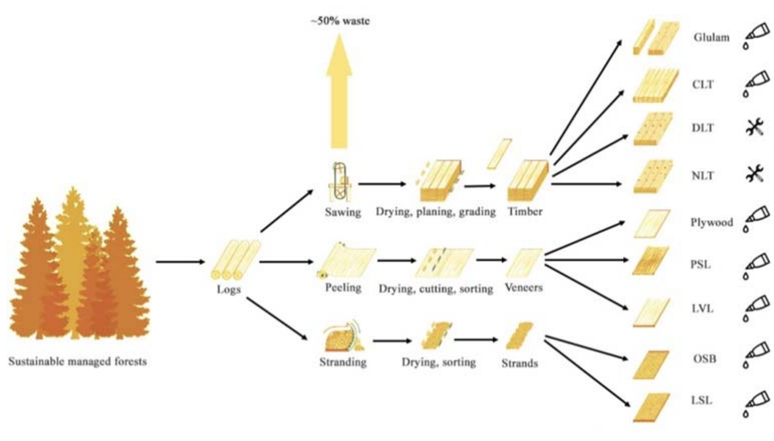

Figure 3 Diagram of the production of the structural timber products as researched, with method of lamination using either glue or mechanical methods (Illustration based on image from Ramage et al. (2017, p. 344)).

According to the zero-waste requirements the material should be fully recyclable or renewable. The adhesives used in many mass-timber products are of synthetic origin and are made from fossil fuels (Messmer, 2015) and have a non-negligible impact on fossil depletion, climate change and human health. Although the adhesive forms a very small percentage of the final product, it does prevent the product from being fully recyclable. The individual timber elements are very difficult to be separated from the glue, especially for the products made out of strands. Larger timber elements can theoretically be separated from the glue, but only on a small scale in laboratories (Scalet, 2015). Products which use any form of mechanical lamination, which are DLT and NLT, are therefore the most suitable candidates for zero-waste timber structures. It should be noted however, that adhesives are still necessary for finger jointing, but this uses drastically less adhesive than laminating entire panels.

This drastically reduces the flexibility of a design, as elements such as beams and columns are not commonly made using DLT and NLT. However, in theory it is possible as shown in (de Lange & van Houten, 2016, pp. 163-167). It is also a possibility that natural resins can be used in the future, such as lignin, tannin, cashew nutshell liquid and castor oil (Messmer, 2015). This would enable all timber products to be used in a zero-waste design. The timber products can also be easily re-used, they can be sawn or milled into new shapes. The products can eventually be chipped or stranded and can be recycled into panels or boards. At the end of life timber can alternatively be incinerated for energy without causing waste or pollution.

IV. Conclusions

Mass-timber structures for extending existing buildings can be a sustainable solution for the increasing urbanization in the world. It is a renewable and zero-waste building material and by reusing the existing building stock, demolition can be prevented. This paper shows that several considerations should be taken into account when designing a zero-waste mass-timber structure for an extension of an existing structure:

First of all the correct materials should be used for a zero-waste structure. Timber is a renewable source, but not all mass-timber products available are fully zero-waste. The adhesives used in most products prevent separating the original materials and are not fully recyclable. Nailed-laminated and dowel-laminated timber however are mechanically laminated. Dowel-laminated timber can be an all wood solution, having the benefits of mass-timber characteristics and being fully reusable and recyclable. DLT is produced in panels and lends itself best for structural solutions which use walls for load bearing and stability. Other products can also be used in an almost zero-waste design, as the adhesives only form a small part of the total product. Bio resins can also form a solution in the future as an alternative for synthetic adhesives.

Secondly, reusing existing structures for extensions prevents the use of new concrete for foundations. A retrofit of an existing structure could offer lower loads than its previous function, allowing for a taller structure. Partial demolition and replacement with mass-timber also allows for taller structures as the material is lighter than traditional building materials such as concrete and masonry. Introducing a more efficient stability system could also enable a larger load capacity. The existing structure can be strengthened using steel reinforcement and steel piling for the foundation.

Thirdly, a building method should be chosen suitable for the extension and for the used mass-timber product. Mass-timber is lightweight compared to concrete and overturning moments form a challenge with increased heights. The structure should therefore be designed with sufficient horizontal stability measures. Suitable methods are cellular structures, a structural core, a structural core with outriggers or a megastructure. Mass-timber can also be combined with fully recyclable metals to form hybrid structures. In the entire design demountable connections should be used for future disassembly. Mass-timber also does not require encapsulation or coating for fire safety, the material can protect itself when designed with a sacrificial charring layer.

References

de Lange, N.A., & van Houten, R.S. (2016). *A Zero-Waste Approach in the Design of Buildings.* (Master Thesis), University of Technology Delft, Delft.

Gonzalez, V.P. (2017). *Tall Timber Extension.* (Master Thesis), University of Technology Delft, Delft.

Green, M. (2017). *The Case for Tall Wood Buildings*. Retrieved from http://thecasefortallwood.com/wp-content/uploads/2017/02/2017-01-24-THE-CASE-FOR-TALL-WOOD-SECOND-EDITION.pdf

Johansson, B., & Thyman, M. (2013). *Strengthening of buildings for storey extension.* (Master Thesis), Chalmers University of Technology, Göteborg.

Messmer, A. (2015). *Life cycle assessment (LCA) of adhesives used in wood constructions.* (Master thesis), Eidgenossiche Technische Hochschule Zurich, Zurich.

Nijsse, R. (2012). *Dictaat Draagconstructies II*. Retrieved from Delft: http://wiki.bk.tudelft.nl/mw_bk-wiki/images/c/c2/Draagconstructies_II.pdf

Papageorgiou, M. (2016). *Optimal Vertical Extension A study on costs and environmental impact for structural engineers.* (Master Thesis), Delft University of Technology, Delft.

Ramage, Michael, Burridge, Henry, Wicher, Marta, Fereday, George, Reynolds, Thomas, Shah, Darshil, . . . Scherman, Oren. (2017). *The wood from the trees: The use of timber in construction* (Vol. 68).

Redling, A. (2018). Construction debris volume to surge in coming years. Retrieved from https://www.cdrecycler.com/article/global-volume-construction-demolition-waste/

Relker, T. (2013). *Adding stories on top of existing buildings.* (Master thesis), Techincal University of Eindhoven, Eindhoven.

Scalet, T. (2015). *Cross Laminated Timber as Sustainable Construction Technology for the Future.* (Bachelor thesis), Helsinki Metropolia University of Applied Sciences, Helsinki.

Serrana, E. (2009). *Limnologen - Experiences from an 8- storey timber building*. Paper presented at the 15. Internationales Holzbau-Forum 09.

The Open University. (2016). Study Session 5 Urbanisations: Trends, Causes and Effects. Retrieved from http://www.open.edu/openlearncreate/mod/oucontent/view.php?id=79940&printable=1

United Nations. (2017). *World Population Prospects: The 2017 Revision, Key Findings and Advance Tables.* Retrieved from https://esa.un.org/unpd/wpp/Publications/Files/WPP2017_KeyFindings.pdf

United Nations. (2018). 68% of the world population projected to live in urban areas by 2050, says UN. Retrieved from https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html

United Nations Environment. (2017). *Global Status Report 2017, towards a zero-emission, efficient and resilient buildings and construction sector*. Retrieved from https://www.worldgbc.org/sites/default/files/UNEP%20188_GABC_en%20%28web%29.pdf

Appendix

As part of:

Designing a zero-waste mass-timber high-rise load-bearing structure

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The University of British Columbia. Brock Commons Tallwood House. Retrieved from
https://sustain.ubc.ca/research/research-collections/brock-commons-tallwood-house

Introduction

This appendix contains the documentation of the studies complementary to the paper *Designing a zero-waste mass-timber high-rise load-bearing structure.* It contains the zero-waste requirements, case studies into mass-timber high-rises, case studies into high-rise extensions and a study into the different mass-timber products available.

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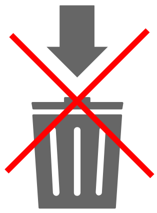
Database 1 Zero-Waste Requirements

This database contains the zero-waste requirements as interpreted from *A Zero-Waste Approach in the Design of Buildings* by de Lange, N.A., & van Houten, R.S (2016).

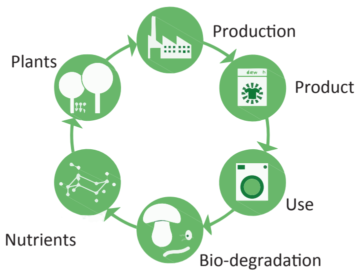
1.1 Primary zero-waste requirements

1



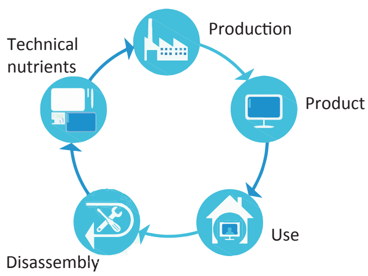
0 kg waste during all (de)construction phases of the building

2A



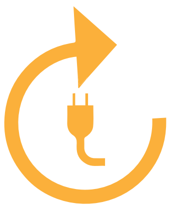
Natural materials must remain in the biological cycle

2B



Metallic and synthetic (and all man-made) materials must remain in the technosphere cycle

3



Reuse of materials should be made possible insuch a way that invested/embodied energy is maintained as much as possible, or can easliy be increased

Information obtained from (de Lange & van Houten, 2016, p. 22):
de Lange, N.A., & van Houten, R.S. (2016). *A Zero-Waste Approach in the Design of Buildings.* (Master Thesis), University of Technology Delft, Delft

1.2 Secondary zero-waste requirements

MATERIALS

2A 2B	Used materials must come from a sustainable, reusable source, respecting embodied energy
1 2A 2B	No polluting, toxic or hazardous materials are used
2A 2B	Used materials should be identifiable after the lifetime use in a building or component to allow for reuse
1 2A 2B	The amount of different materials used should be kept to a minimum

CONNECTIONS

1 2A 2B	Inseparable connections must be avoided, unless if it is made out of the same material
1 2A 2B	The amount of different connectors and connections should be kept to a minimum
3	Joints, connectors and components have to withstand repeated use

COMPONENTS

1	The amount of (different types of) components should be minimized
2A 2B 3	Provide permanent identification of component types
3	Design for maximum standardization or repitition
3	Design multi-functionable components to integrate systems

LEGEND

1 2A 2B 3	Number corresponds to primary zero-waste demands numbers
RED	Hard demand
BLUE	Strong suggestion
GREEN	Suggestion

ASSEMBLY AND DISASSEMBLY

1 2A 2B 3	The complete structure, connections and components should designed for disassembly without the use of destructive methods
1 3	Methods of disassembly should be made clear perma-nently
1	The hierarchy of the building should respeect the expected lifespan of the individual parts
1	Means on handling and locating components during assembly and disassembly should be provided
1	No specialized tools should be developed or used for (dis)assembliing the building
1 3	Modularity and an open building system should be used
1 3	The most reusable parts should be the most accessible
1 2A 2B	The system designed should be able to be prefabricated

Information obtained from (de Lange & van Houten, 2016, p. 24):
de Lange, N.A., & van Houten, R.S. (2016). *A Zero-Waste Approach in the Design of Buildings.* (Master Thesis), University of Technology Delft, Delft

Database 2 — Mass-Timber High-Rises

This database contains case studies of existing mass-timber high-rises. The selection is made based on height, building method and stability system. Each case-study has a different structural method in order to examine the different possibilities. The information is obtained using literature study, analysis of drawings and examination of construction photos. The following projects are included:

Tamedia Office Building	Portal structure
Murray Grove	Cellular structure
TREET	Core with outriggers in combination with secondary cellular structure
Brock Commons Tallwood House	Core structure with perimeter beams
Mjøstårnet	Megastructure

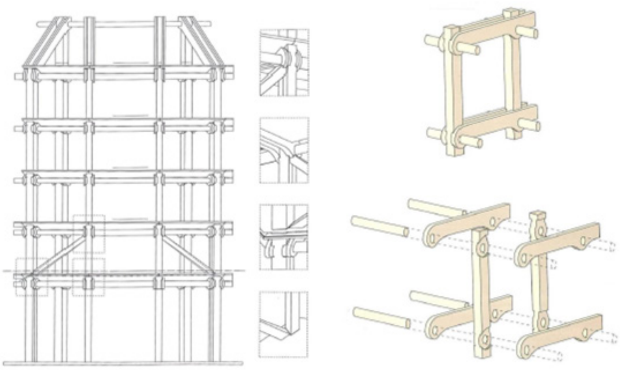
2.1 Tamedia Office Building

The Tamedia Office Building in Zurich by architect Shigeru Ban has an innovative rigid post and beam structure with spans of 5,45x3,2m and 5,45x10,98m. The structure consists of timber frames with 4 columns and 5 double beams supporting the floors. The double beams span the total width of the building, intersecting the columns. Oval beams connect the columns laterally to each other and the existing building, creating a stable frame. The timber members are over-dimensioned for fire and to prevent progressive collapse.

Didier Boy de la Tour. Tamedia Office Building.
Gonzalez, V.P. (2017). *Tall Timber Extension.* (Master Thesis), University of Technology Delft, Delft.
Hill, J. (2014). Tamedia's Timber Structure. Retrieved from https://www.world-architects.com/en/pages/products/tamedia-timber-structure
Tamedia Office Building / Shigeru Ban Architectus. (2014). Retrieved from https://www.archdaily.com/478633/tamedia-office-building-shigeru-ban-architects

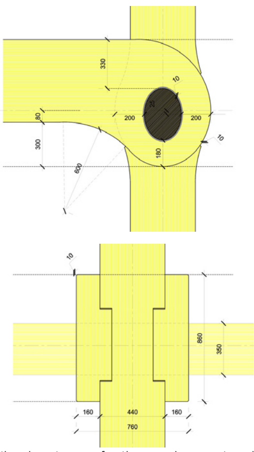
Year	2013
Location	Zurich, Switzerland
Architect	Shigeru Ban
Height	23m
# of storeys	7
Structure	Glulam columns and beams with lightweight floor system, stability provided by existing structure
Foundation	Concrete basement
Fire	Sacrificial layer Sprinkler systems
Zero-waste	Yes, except floor build up

The Tamedia Office Building in Zurich (Didier Boy de la Tour)

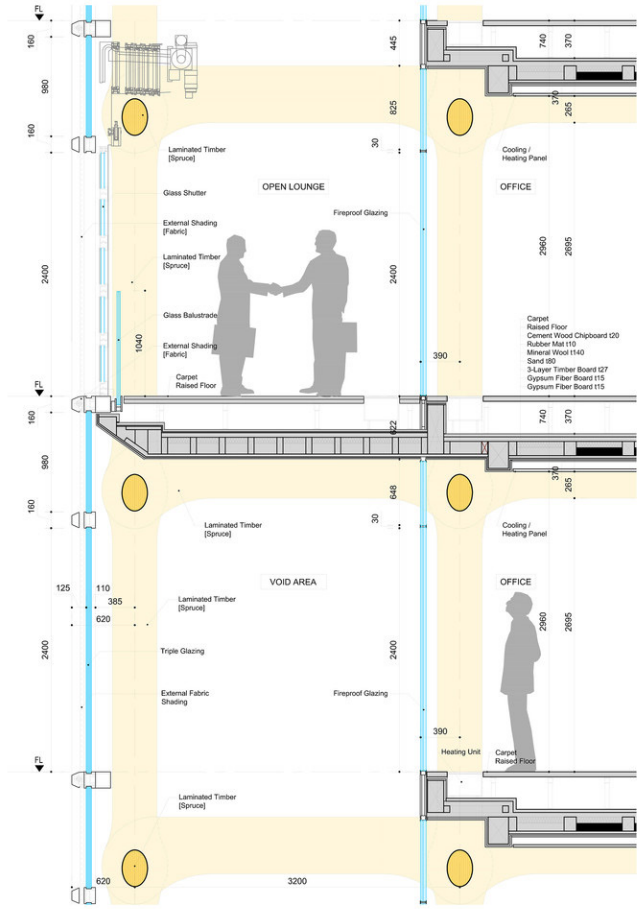


Section of the timber structure, which is a portal frame with continuous columns. The structure is made in bays from the existing structure, enabling a stable structure during construction (Gonzalez, 2017, p37)

Picture of the spruce pine column to beam connection, using a large LVL dowel of beech for a rigid connection (Hill, 2014)



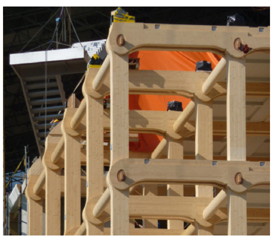
Detail drawing of the column to beam connection ("Tamedia Office Building / Shigeru Ban Architects," 2014)



Section drawing of the building ("Tamedia Office Building / Shigeru Ban Architects," 2014)

Overall Detail

The construction in process, the building was erected bay by bay ("Tamedia Office Building / Shigeru Ban Architects," 2014)



The glulam superstructure ("Tamedia Office Building / Shigeru Ban Architects," 2014)

Transverse oval beams connect the portals rigidly to the existing structure ("Tamedia Office Building / Shigeru Ban Architects," 2014)

Close up of the structural detail in the finished building ("Tamedia Office Building / Shigeru Ban Architects," 2014)

2.2 Murray Grove

The Murray Grove or Stadthuis building in London by Waugh Whistleton Architects was the tallest timber structure in the world in 2009. CLT panels are used for the floors and walls and form a cellular honeycomb structure which forms a stable whole. The elements are robustly designed, which means that a wall could span 2 levels for example or a floor panel could span twice its length, to prevent progressive collapse. The CLT panels have a sacrificial layer with an additional plasterboard encapsulation for fire protection. The CLT panels are connected using brackets and screws.

Grondahl, M. (2012). Building With Engineered Timber. Retrieved from https://archive.nytimes.com/www.nytimes.com/interactive/2012/06/05/science/0605-timber.html?_r=0

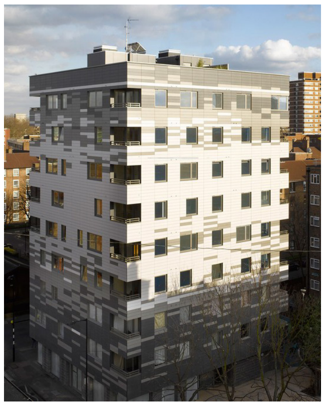
KLH. Stadthaus Murray Grove, London/UK. Retrieved from https://www.behance.net/gallery/12747107/Stadthaus-Murray-Grove-LondonUK

NZ wood. Stadhaus - Murray Grove Tower. Retrieved from http://www.nzwood.co.nz/wp-content/uploads/2013/06/Murray_Grove_01-525x295.jpg

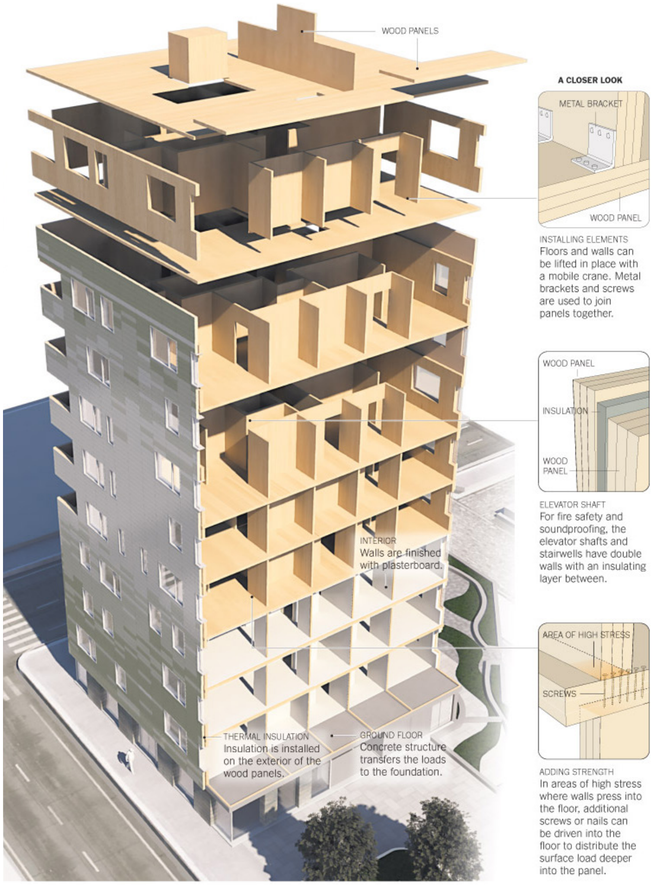
TRADA Technology. (2009). *Stadthaus, 24 Murray Grove, London: Eight storeys of apartments featuring cross-laminated timber panels.* Retrieved from https://eoinc.weebly.com/uploads/3/0/5/1/3051016/murray_grove_case_study.pdf

Waugh Whistleton Architects. (2009). Murray Grove The Original Timber Tower. Retrieved from http://waughthistleton.com/murray-grove/

Year	2009
Location	Hackney, London
Architect	Waugh Thistleton Architects
Height	30.3m
# of storeys	9
Structure	CLT walls and floors in a cellular honeycomb structure using the platform building method
Foundation	Reinforced concrete ground floor
Walls	128mm thick CLT panel
Floors	146mm thick CLT panel
Fire	Sacrificial layer Encapsulation with plasterboard panels
Zero-waste	Yes (from first floor up)

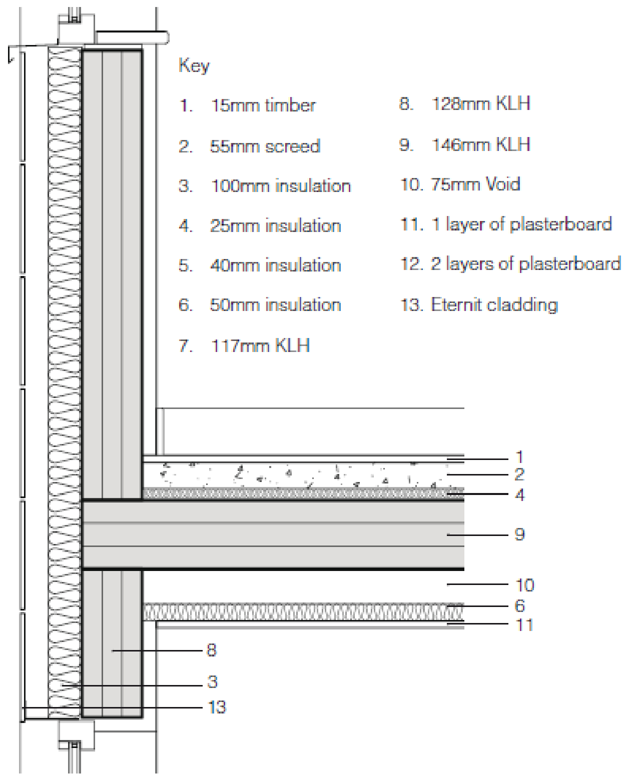


The Murray Grove or Stadthaus building in London (Waugh Whistleton Architects, 2009)



The buidling is made stable by a cellular honeycomb structure. The walls and floors are designed with redundancy to prevent progressive collapse (Grondahl, 2012).

Detail A:
Section at external wall

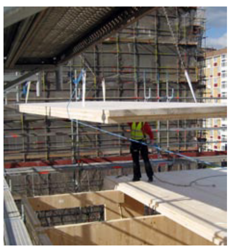


Detail section of a representative floor and wall join. The walls are stacked, also known as the platform method, additional screws and nails are used to distribute the loads into the panel below. Plasterboard is added as encapsulation for additional fire safety (TRADA Technology, 2009, p.6).

Overall ⟷ Detail

The cellular structure is raised floor by floor (NZ wood)

Photo illustrating the bracket connections and the stairwell (KLH)



The platform building method is used to stack the floors and walls (TRADA Technology, 2009, p.5)

Walls are connected to the floor using brackets (TRADA Technology, 2009, p.5)

2.3 TREET

The Treet building is situated in Bergen, Norway and is a result of an ambition to make a high-rise building using timber as the structural material. The building has a load bearing structure made out of large glulam trusses with two 'power storeys' made out prefabricated concrete slabs on glulam trusses. Prefabricated modules of CLT with the actual dwellings are situated on the foundation, and the two 'power storeys'. The modules have a seperate load bearing structure from the main structure.

Abrahamsen, R.B. (2015). Treet Ext Full. Retrieved from https://images.skyscrapercenter.com/building/treet-ext-full_(c)rune__abrahamsen.jpg

Abrahamsen, R.B., & Malo, K.A. (2014). Structural Design and assembly of "Treet" - a 14 storey timber residential building in Norway. *New Zealand Timber Design*, 22(3).

Artec. (2017a). Detail of glulam beams. Retrieved from http://www.buildup.eu/sites/default/files/detail_of_glulam_beams_c_sweco_artec.png

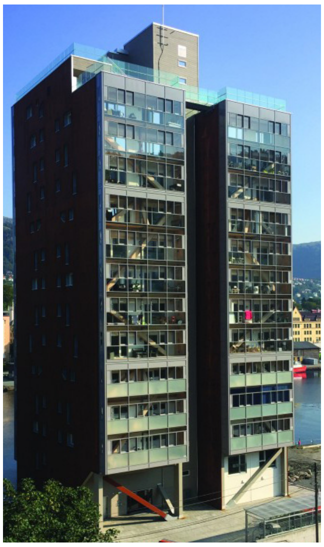
Artec. (2017b). Load bearing structure and wooden prefabricated modules. Retrieved from http://www.buildup.eu/en/practices/cases/treet-wooden-high-rise-building-excellent-energy-performance

Artec. (2017c). Metal and glass cladding works on facade. Retrieved from http://www.buildup.eu/sites/default/files/metal_and_glass_cladding_works_on_facade_c_sweco_artec.png

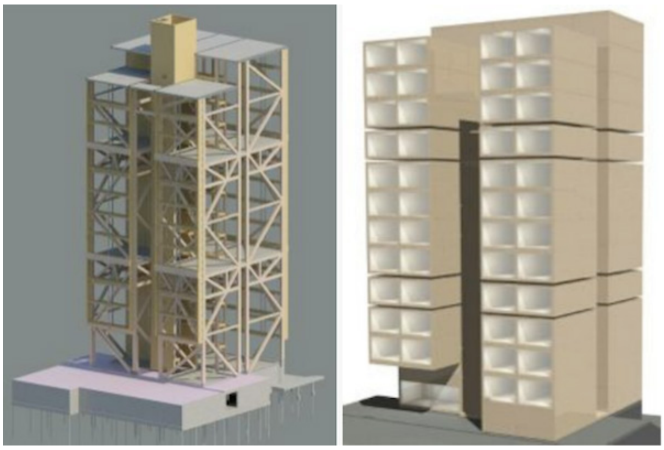
Guajardo, A.E.M. (2016). *Carbon Footprint of the Tallest Timber Building.* Universitat Politecnica de Valencia, Valencia.

Kleppe, H.O., & Abrahamsen, R.B. (2016). *Construction of Treet - How and Why.* Paper presented at the International Wood Symposium, Vancouver.

Year	2015
Location	Bergen, Norway
Architect	Artec
Height	52.8m
# of storeys	14
Structure	Core with outriggers and prefab concrete floor, glulam truss frame, CLT modules
Foundation	Concrete piles and ground level
Fire	Fire resistant lacquer Sprinkler systems Sacrificial layer Fire stops in façade every 2nd storey
Typical column	495x495mm, 405x650mm
Typical truss	405x405mm
Zero-waste	No

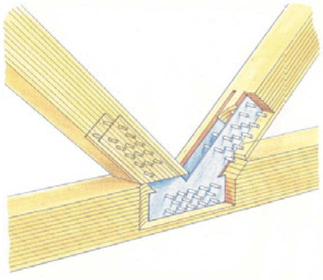


The finished building (Abrahamsen, 2015)

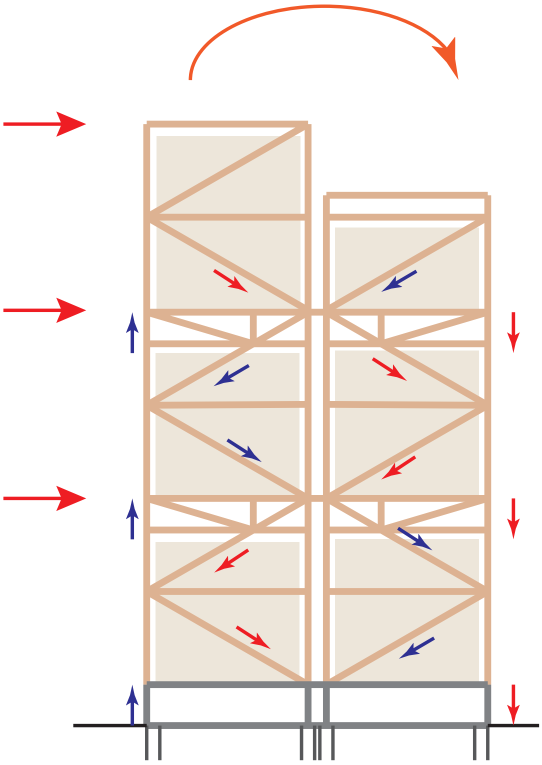


The prefabricated modules with the dwellings (right) are installed into the superstructure (left) which provides structural support for the entire building (Artec, 2017b)

Steel inserts are used to join the glulam members (Guajardo, 2016, p. 19)

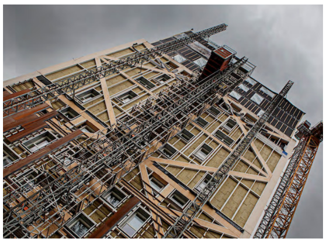


Detail drawing of the steel nodes, protected from fire by the wood(Abrahamsen & Malo, 2014, p. 6)



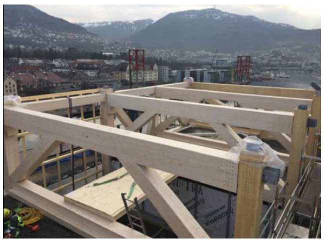
The structure behaves like a giant truss, spreading the loads induced from the wind across a large distance, reducing the resulting forces in the foundation. The apartments are seperate structures and are behind the facade, they do not contribute to the stability and do not have to withstand the forces of the wind due to the cover of the facade.

Overall ⟷ Detail



The cladding of the building is installed using metal frames (Artec, 2017c)

Close up of the glulam truss structure (Artec, 2017a)



Detail of the glulam trusses for the 'power storey' (Kleppe & Abrahamsen, 2016)

Finished detail of the glulam trusses (Kleppe & Abrahamsen, 2016)

2.4 Brock Commons Tallwood House

The Brock Commons Tallwood House is located in Vancouver , Canada. It is a hybrid timber structure composed of reinforced concrete on the ground floor and first floor, two reinforced concrete cores and a glulam column structure with CLT floors. Each floor is stiffened with a concrete topping and a steel perimeter beam, which also supports the envelope. The CLT floor panels are point supported, using a steel node at the columns. The loads of the columns are directly transferred to the next column with this method without crushing the weak edges of the slabs.

Fast, P. (2016). *Case Study: An 18-storey tall mass timber hybrid student residence at the University of British Columbia.* Paper presented at the Internationales Holzbau-Forum IHF 2016. http://www.forum-holzbau.com/pdf/37_IHF_2016_Fast.pdf

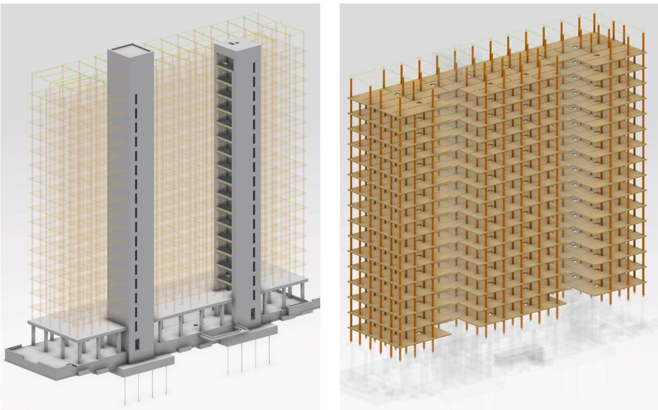
Hasan, Z.G. (2017). Inside Vancouver's Brock Commons, The world tallest mass timber building.

Metras, J., Austin, R., & Fraser, K. (2016). Introducting Brock Commons: Looking up tot the world's tallest contemporary wood building. Retrieved from https://www.constructioncanada.net/introducing-brock-commons-looking-up-to-the-worlds-tallest-contemporary-wood-building/

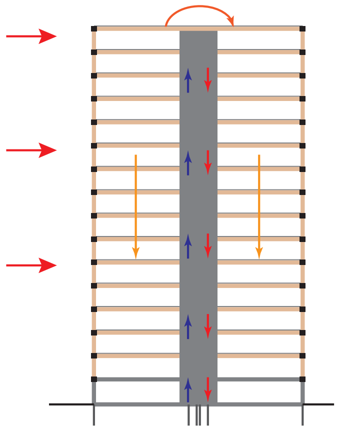
Poirier, E., Moudgil, M., Fallahi, A., Staub-French, S., & Tannert, T. (2016). *Design and construction of a 53-meter-tall timber building at the University of Columbia.* Paper presented at the WCTE 2016 World Conference on Timber Engineering, Vienna. http://www.proholz.at/fileadmin/proholz/media/documents/Thomas-Tannert.pdf

Year	2017
Location	Vancouver, Canada
Architect	Acton Ostry
Height	53m
# of storeys	18
Structure	Reinforced concrete cores and steel perimeter beam. PSL columns below the 5th storey and glulam columns above, CLT floors with concrete topping for diaphragm
Foundation	Concrete piles and ground level of concrete, raft slab under cores
Fire	Full encapsulation Sprinkler systems Sacrificial layer
Typical column	495x495mm, 405x650mm
Typical floor	169mm thick
Zero-waste	No

The Brock Common Tallwood House in Vancouver (Hasan, 2017)

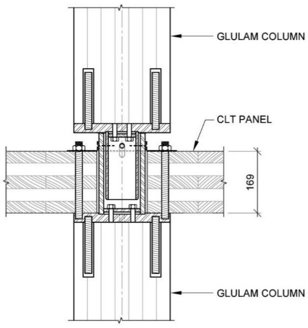


The concrete structure shown on the left provides the main stability, on the right the CLT panels and the glulam columns are shown which provide the main load bearing structure (Fast, 2016).

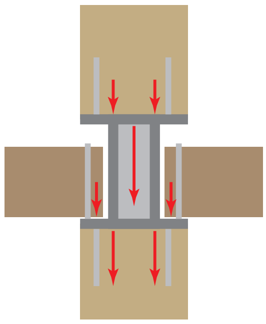


The reinforced concrete cores provide the stability of the structure. The perimeter steel beams (drawn in black) together with the concrete topping of the floor provide a stiff diaphragm to connect the floors to the cores, while the concrete also provides additional deadweight to prevent overturning.

Picture of the column floor connection (Poirier, Moudgil, Fallahi, Staub-French, & Tannert, 2016)



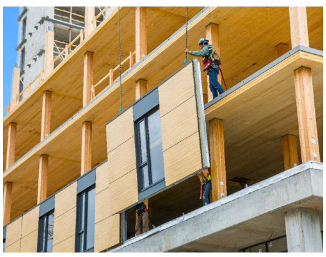
Typical detail for the connection of the columns with the floors using a steel node (Fast, 2016).



The flow of the forces sketched into the connection detail. The steel intermediary connects the columns directly, preventing the CLT panels from being crushed at the edges.

Overall ⟷ Detail

The construction in process, showing the build up of the structure (Metras, Austin, & Fraser, 2016)



The facade is placed in prefab panels during construction to quickly seal the building (Fast, 2016).

The timber load bearing structure, prefabricated with integrated services (Fast, 2016).

The structure could be erected by hand due to the light weight nature of timber (Fast, 2016).

2.5 Mjøstårnet

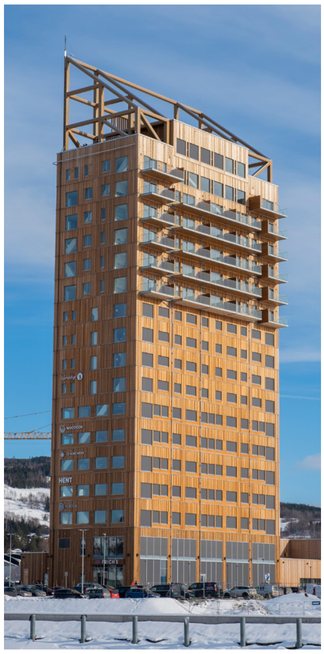
The Mjøstårnet building in Brumenddal is at the time of writing the tallest timber structure in the world. It houses offices, apartments, hotel rooms, restaurants and conference rooms. The structure consists out of large glulam trusses. The glulam is prefabricated at the factory and assembled into large trusses at the building site and subsequently hoisted into position. Steel nodes are used to connect the glulam together. The steel nodes are recessed in the timber to be protected in the case of fire. The elevator shafts and the stair cases are made from CLT and do not contribute to the structural stability of the building. The top floors of the building are made from concrete to reduce the sway of the building.

Abrahamsen, R. (2017). *Mjøstårnet – Construction of an 81 m tall timber building.* Paper presented at the Forum Holzbau Garmisch 17.

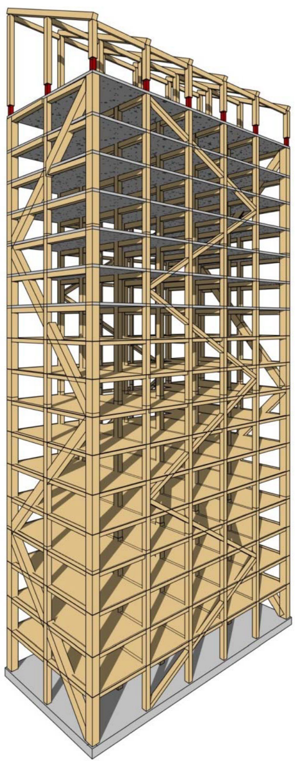
Abrahamsen, R. (2018). *Mjøstårnet - 18 storey timber building completed.* Paper presented at the Internationales Holzbau-Forum IHF 2018.

Block, I. (2019). Mjøstårnet in Norway becomes world's tallest timber tower. Retrieved from https://www.dezeen.com/2019/03/19/mjostarne-worlds-tallest-timber-tower-voll-arkitekter-norway/W

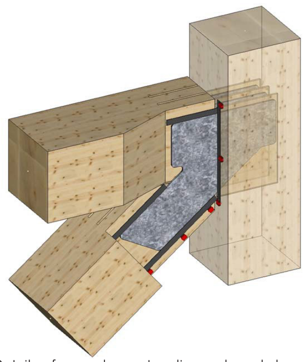
Year	2019
Location	Mjøstårnet, Brumenddal
Architect	Voll Arkitekter
Height	85.4m
# of storeys	18
Structure	Glulam columns, beams and diagonals. CLT shafts for elevators and stairs, not connected to super structure. Wooden slabs of glulam and LVL in the first 10 floors, concrete decks for upper floors (to reduce sway)
Foundation	Concrete slab with piles for compression and tension
Columns Typical	GL30c and GL30h 725 x 810mm, 625 x 625 mm
Corner	1485 x 625mm
Forces	
Max compressive	11500 kN
Max tension	5500 kN
Beams	GL30c and GL30h
Timber floor	395 x 585mm, 395 x 675mm
Concrete floor	625 x 858mm, 625 x 720mm
Diagonal	625 x 720 mm
Fire	Sacrificial layer Sprinkler systems Fire retardant painting Firestops in the façade
Zero-waste	No



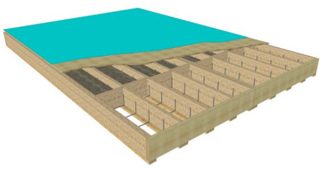
Mjøstårnet, Brumenddal in Norway (Block, 2019)



The timber superstructure consisting of glulam columns, beams and diagonals, and timber floors. Note on the top floors concrete is used to reduce sway of the building (Abrahamsen, 2017).



Detail of a column to diagonal and beam connection. A steel node is used to connect the members together. The node is recessed in the timber to protect it from fire. An additional protective intumescent fire strip is applied in the recess (Abrahamsen, 2017).



The timber floors are made from glulam girders. An LVL plate is glued to the girders and rockwool is kept in place by steel brackets for fire resistance. These elements use less wood compared to CLT decks (Abrahamsen, 2017)

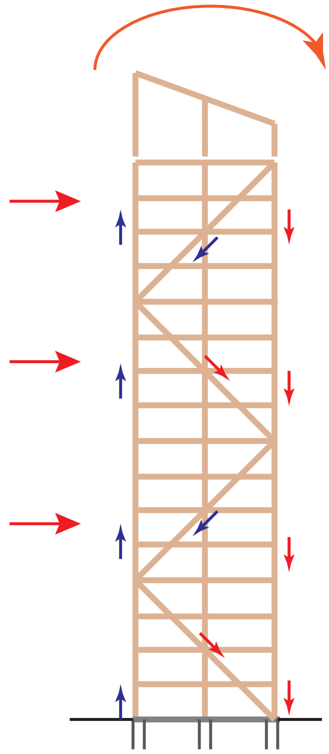
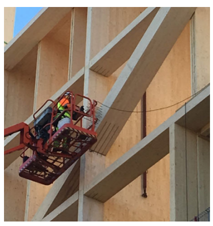


Diagram of the structure. The structure is basically a large truss in all four directions. Maximizing the distance on which the moment acts to decrease the forces in the foundation.

Overall ⟷ Detail

The construction in process showing the large glulam elements forming stable trusses (Abrahamsen, 2018)

The glulam was erected in large pieces, which were assembled together onsite (Abrahamsen, 2018)



Construction worker fastening bolts to connect the glulam element to the steel node (Abrahamsen, 2018)

Close up of the finished connection detail (Abrahamsen, 2018)

Database 3 High-Rise Extensions

This database contains case studies of existing high-extensions. The projects are selected based on the information available and the amount of added floors had to be more than 2. The information is obtained using literature, by examining the photos of the construction or by analysing of drawings (if present). The following buildings are included in the study:

Groot Willemsplein	New structural cores for stability introduced and change of function
Westerlaantoren	Outrigger added to existing structural core and strengthening of foundation
Fahle House	Change of function and new structural cores for stability
Karel Doorman	New structural cores for stability introduced and change of function

3.1 Groot Willemsplein

This vertical extension is built on an old distillery building from 1946, it was the second renovation of the building after it was transformed in the 70's into an office building. The building was extended by 3 additional floors in 2013.

The existing load bearing structure dated from the original building and the concrete facade was added in the first renovation, replacing the original masonry facade. The original building was designed for a load of 15 kN/m^2, a high load due to the former function. An office building generally requires 3kN/m^2 of load bearing capacity.

The stability of the building was provided by the rigid concrete frame. By adding two new reinforced concrete cores additional load bearing capacities were realised in the columns. This allowed for the extension of the building using a steel frame and concrete holow core slabs. The original foundation could be used because of the high capacity. Some additional piles were placed under the new cores using screw injection piles and heavy pile caps (Papageorgiou, 2016).

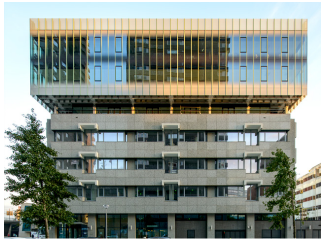
AKS bouw. Groot Willemsplein. Retrieved from http://www.aksbouw.nl/portfolio/groot-willemsplein/

Papageorgiou, M. (2016). *Optimal Vertical Extension.* (Master Thesis), University of Technology Delft, Delft.

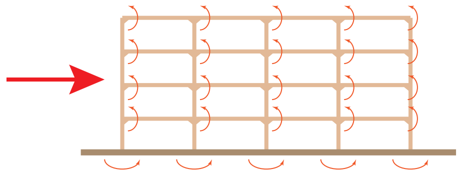
Pieters Bouwtechniek. (2019). Groot Willemsplein. Retrieved from https://www.pietersbouwtechniek.nl/projecten/groot-willemsplein

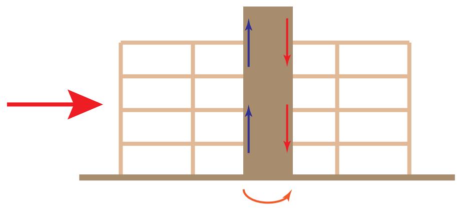
Skyscrapercity. (2012). Retrieved from https://www.skyscrapercity.com/showthread.php?t=1477915&page=13

Year extended	2013
Original year built	1946
Architect	DAM & Partners Architecten
Original height	ca. 16m
New total height	ca. 30m
Original # storeys	5
New # storeys	8
Structural material	Steel + hollow core floors
Structural system	Reserves in the existing structures and with addition of a new stability system more load bearing capacity became available. Lightweight steel structure with 2 concrete cores for stability
Foundation	Use of existing piles and under new cores a foundation of screw injection piles and heavy pile caps



The finished building (AKS bouw).





The original portal structure was made stable by the internal moments in the beams and columns. By adding a core the columns no longer had large internal stresses, and could thus support more weight.

Two concrete cores, a small one for elevators, services and emergency stairs, and a large one for an atrium, were added to provide the stability and free up additional loading capacity of the existing concrete structure (Skyscrapercity, 2012).

On top of the existing structure a lightweight steel frame was used with hollow concrete floor with a diaphragm concrete layer on top for stability (Skyscrapercity, 2012)

Parts of the existing floors and beams were demolished to make way for the new core with the atrium and the stairwell (Pieters Bouwtechniek, 2019)

Overall ⟷ Detail

Topping out of the structure with the facade going up (Skyscrapercity, 2012)

Steel frame top up in construction (Skyscrapercity, 2012)

Close up of the detail of the steel columns on top of the renovated building (Pieters Bouwtechniek, 2019)

3.2 Westerlaantoren

The Westerlaantoren is an extension of the old office building of Vopak in Rotterdam. The building was to be renovated into a mixed use function of office space and dwellings. The tower was stripped of the facade and the highest 2 floors were demolished. The first four floors cantilevered outwards and were also demolished to fit the footprint of the tower.

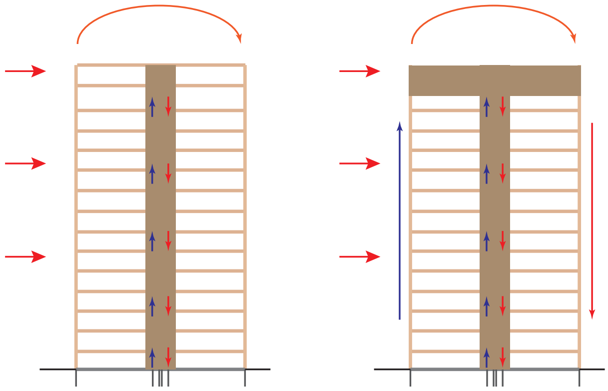
After the demolition, the towers base was strengthened. Additional concrete walls were placed in the basement to spread the loads to the solid foundation plate, which in turn is supported by concrete piles. Some columns were also strengthened and the walls on the corners were extended to the top floor.

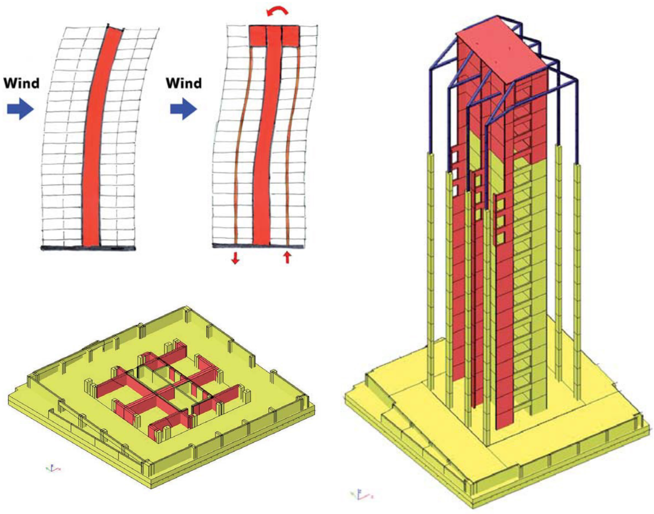
In addition the new extension was created to form an outrigger structure (van der Beek). This creates a different moment line in the overall structure and connects the columns on the perimeter with the core, to function as a whole. This reduces the overall moment in the structure and thus the forces in the foundation. The outrigger was made using steel columns and beams. The floors of the extension were made using lightweight bubble-deck concrete floors (van der Beek).

Ector Hoogstad Architecten. Westerlaantoren luxury apartments and offices Rotterdam. Retrieved from https://www.ectorhoogstad.com/en/projects/westerlaantoren-luxury-apartments-and-offices-rotterdam
Schamp, M. (2010). Een tweede leven voor de Westerlaantoren. *Funderingsdag 2010 Special, december 2010.*
Skyscrapercity. (2012). Rotterdam: Westerlaantoren (Vopak). Retrieved from https://www.skyscrapercity.com/showthread.php?t=25151&page=83
van der Beek, P. Van kantoortoren tot kantoor- en appartemententoren. *Stedenbouw 686*, 40-41.

Year extended	2012
Original year built	1959
Architect	Ector Hoogstad Architects
Original height	61 m
New total height	76 m
Original # storeys	17
New # storeys	20
Structural material	Steel, concrete bubble-deck floors
Structural system	Demolition 2 top storeys, create 7 new storeys. Outrigger structure to counter the increase in moment load. Steel columns and beams used for the outrigger, reinforced concrete extension of the core and
Foundation	Use of existing piles, add new concrete walls in basement to spread the loads evenly over the existing piles. Walls above the ground level strengthened.


The Westerlaan Toren (Ector Hoogstad Architecten).


The outrigger makes the structure stiffer by enabling the columns to add to the overall stiffness, in effect creating a larger distance on which the moment acts.



In order to make the extension, the 2 top floors of the original Vopak building were demolished together with the cantilevered floors on the lower 4 floors. An outrigger was introduced for the extension to spread the loads over the structure, and thus the loads on the.foundation. In addition in the basement additional floors were added to spread the loads evenly on the solid foundation plate (Schamp, 2010)


On the left the old Vopak building, in the middle the stripped building, on the right the finished renovated Westerlaantoren

Start

Finished


Start of the extension with the steel bases (Skyscrapercity, 2012)


Steel columns are used for the load bearing structure and the outrigger (Skyscrapercity, 2012)


Connection of the steel diagonals of the outrigger with the concrete core (Skyscrapercity, 2012)

3.3 Fahle House

The Fahle House, designed by KOKO architects, is built on top of an old cellulose and paper factory in Talinn. The tall boiler house was originally built in 1926 and designed by architect Erich Jacoby using limestone and concrete. The new extension houses 6 storeys with apartments, the existing boiler house is renovated to also house dwellings. The lower part of the building is used for offices and services Lige, C.D. (2015).

The extension is realised by demolishing the upper layer of the old boiler house and removing part of the floors in the existing building. Within the existing buildings new reinforced concrete walls were added to house the vertical circulation and to also provide stability for the new extension. The load bearing structure was extended and connected to the old structure using reinforced concrete.

Emporis. (2016). Fahle Maja. Retrieved from https://www.emporis.com/buildings/241174/fahle-maja-tallinn-estonia

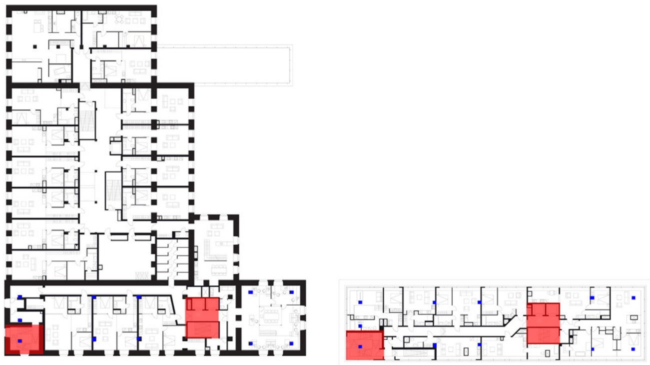
KOKO Architects. (2012). Fahle 1926 Maja 2006. Retrieved from https://issuu.com/kokoarchitects/docs/fahle_book

KOKO Architects. (2016). Fahle House / KOKO architects. Retrieved from https://www.archdaily.com/780385/fahle-house-koko

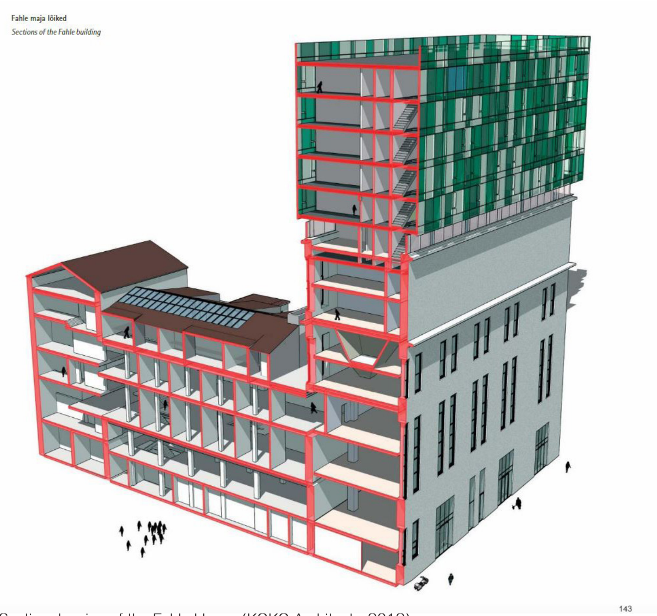
Lige, C.D. (2015). The Fahle Building in Talinn, Estonia 1926. Retrieved from http://blueiskewl.blogspot.com/2015/06/the-fahle-building-in-tallinn-estonia.html

Year extended	2007
Original year built	1926
Architect	KOKO Architects
Original height	ca. 30 m
New total height	55 m
Original # storeys	8
New # storeys	14
Structural material	Steel, reinforced concrete
Structural system	Lightweight steel structure on top of the existing rigid concrete frame and limestone walls. The extension is supported by reinforced concrete beams.
Foundation	Use of existing foundation

The Fahle House in Talinn (Lige, 2015)



The floor plan of the third (in the existing building) and the eight floor (of the extension) shows the extension of the existing concrete columns in blue. Also the vertical circulation is enveloped in concrete cores, which provides the stability for the extension (KOKO Architects, 2016), shown in red.



Section drawing of the Fahle House (KOKO Architects, 2012).

Part of the old floors were demolished and in place new reinforced concrete was poured in situ to create the new cores and to extend the existing columns into the extension above (KOKO Architects, 2012).

Start ⟷ Finished

The existing building

The top of the existing building was removed and replaced with the extension (Emporis, 2016)

The completed structural extension (Emporis, 2016)

Cladding is mounted on the structural skeleton (Emporis, 2016)

3.4 Karel Doorman

The Karel Doorman building was originally named the Ter Meulen, designed by Van den Broek & Bakema and was built in 1951. When it was designed a extension for 1 floor was taken into account. In the late 1970's the building was renovated and 2 floors were added. In 2003 it was decided to renovate the buiding to its original state and to add a vertical extension of 16 storeys with apartments (Ibelings & van Tilburg, 2013).

The load bearing structure was revealed to have additional capacity (Papageorgiou, 2016). This could be enabled by creating a new stability system. The original structure was designed with rigid portals. Two new concrete cores would take op the lateral stability which unloaded the original concrete cores of their moment loads, enabling higher compressive loads in the columns.

An ultra light weight building system using steel was used to construct the 16 storeys, timber was used for the flooring. In total the apartments weigh 250kg/m2 with an extreme live load of 175 kg/m2 on one floor and 70 kg/m2 on the other floors. The apartments are made out of metal stud frames as separate boxes from the main load bearing structure (Nationale Staalprijs, 2012).

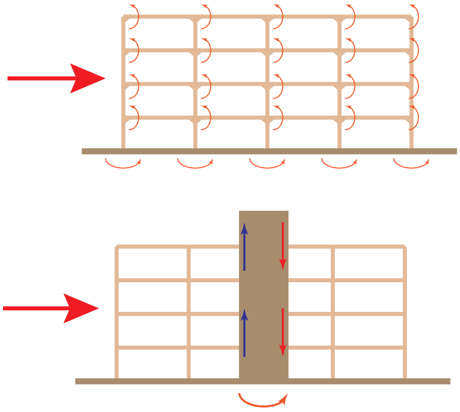
Ibelings, M., & van Tilburg, A. (2013). *De Karel Doorman Rotterdam.* Retrieved from https://www.dearchitect.nl/projecten/nominatie-arc13-architectuur-de-karel-doorman-rotterdam

Nationale Staalprijs. (2012). Woongebouw De Karel Doorman. Retrieved from https://www.nationalestaalprijs.nl/archief/2012/projecten/woningbouw/karel-doorman

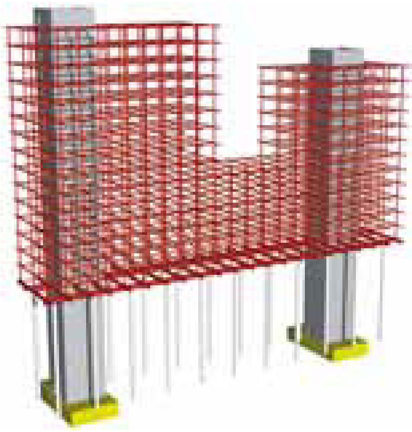
Papageorgiou, M. (2016). *Optimal Vertical Extension A study on costs and environmental impact for structural engineers.* (Master Thesis), Delft University of Technology, Delft.

Year extended	2013
Original year built	1951
Architect	Ibelings van Tilburg Architecten
Original height	ca. 20m
New total height	70m
Original # storeys	6
New # storeys	20
Structural material	Steel
Structural system	Concrete core for stability with steel post and beam structure for
Foundation	Original foundation with modifications to distribute loads evenly

The finished building on top of the old Ter Meulen building (Ibelings & van Tilburg, 2013).

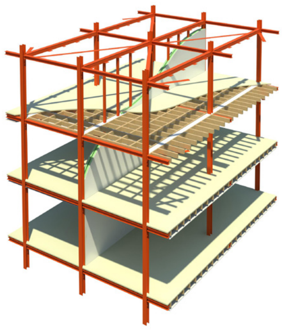


The original portal structure was made stable by the internal moments in the beams and columns. By adding a core the columns no longer had large internal stresses, and could thus support more weight.

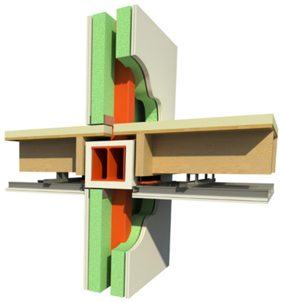


The main load bearing structure is made out of steel. This is supported by an intermediary steel structure which spreads the loads to the existing concrete columns. The stability is provided by the concrete cores (Ibelings & van Tilburg, 2013).

Close-up of the facade, which is made with timber cladding, steel consoles with timber flooring for the balconies and a glass outer skin (Ibelings & van Tilburg, 2013).

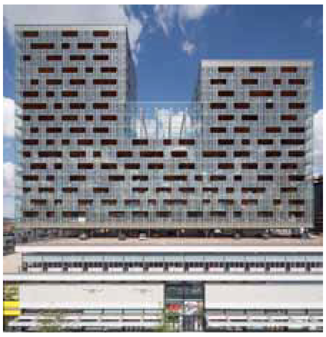


3D section of the steel structure with flooring on the apartment floors (Nationale Staalprijs, 2012)



Detail of the floor and apartment walls with the steel structure (Nationale Staalprijs, 2012)

Overall ⟷ Detail



Front picture of the Karel Doorman buidling (Ibelings & van Tilburg, 2013)

Construction of the extension with the concrete cores and steel structure (Ibelings & van Tilburg, 2013)

Close up of the steel column and beam structure of the extension (Nationale Staalprijs, 2012)

Close up of the column-beam-floor detail (Nationale Staalprijs, 2012)

Database 4 Mass-Timber Products

This database contains a study into mass-timber products. All commonly used mass-timber products are studied, including some panel products which are used with mass-timber panels (such as OSB and plywood). The information is obtained using literature study, and information prodvided by producers and manufacturers. The following products are included in this study:

Sawn Timber or Lumber
Glued Laminated Timber (Glulam)
Cross Laminated Timber (CLT)
Nail Laminated Timber (NLT)
Dowel Laminated Timber (DLT)
Laminated Veneer Lumber (LVL)
Parallel Strand Lumber (PSL)
Plywood
Laminated Strand Lumber (LSL)
Oriented Strand Board (OSB)

Sawn Timber or Lumber

Sawn timber or lumber is sawn from the log of a tree. The log can be sawn in different ways which can effect the strength and look of the pieces. The lumber can be sawn rectangular or square. Different species of trees have different strengths, with the main difference between soft and hard woods. In Europe a classification is made to grade different types of timber for strength. Sawn timber is limited in its size, because it cannot exceed the dimension in which a tree grows. Also the larger the lumber, the more defects and inconsistencies the product will have. It will also effect the drying process, the bigger the more moisture it will contain (Canadian Wood Council, 2019). The method of sawing the lumber also influences the quality of the product: plain, rift and quarter sawn are distinguished. Other methods are also possible such as cant sawn, grade sawn, back sawn and radial sawn.

Canadian Wood Council. (2019). Solid-Sawn Heavy Timber. Retrieved from http://cwc.ca/how-to-build-with-wood/wood-products/mass-timber/solid-sawn-heavy-timber/

Florian, E. (2016). Stadshoutp. Retrieved from https://www.architectinamsterdam.nl/projects/stadshoutpaviljoen/stadshoutp/

Harrop - Procter Forest Products. Rough-Sawn Lumber. Retrieved from https://hpcommunityforest.org/wp-content/uploads/2013/07/IMG_07591.jpg

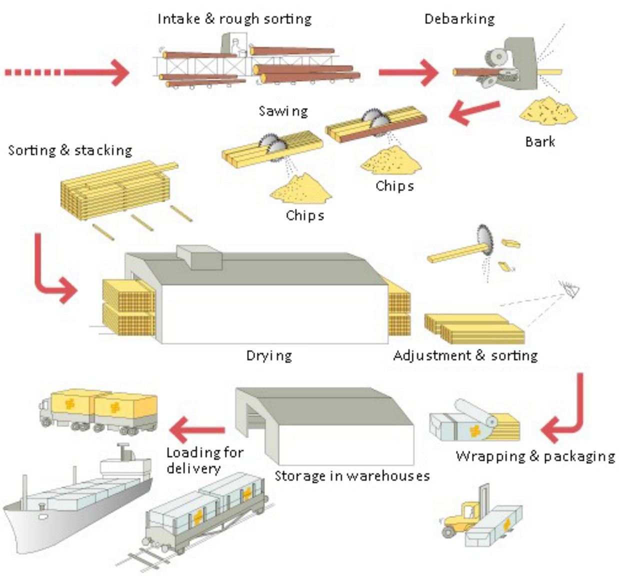
Nicholson, C. (2013). How logs are turned into boards. Retrieved from https://www.core77.com/posts/24890/how-logs-are-turned-into-boards-part-1-plainsawn-24890

Speck, L. (2019). Sakyamuni Pagoda. Retrieved from https://larryspeck.com/photography/sakyamuni-pagoda/

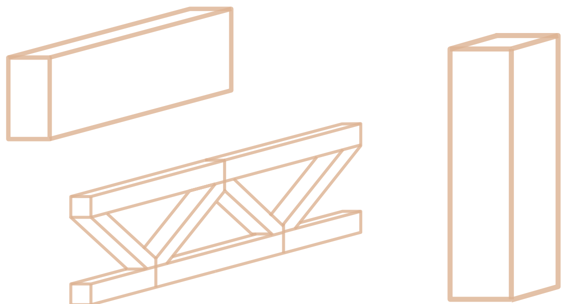
Swedishwood. The sawmill process from forest to sawn wood product. Retrieved from https://www.swedishwood.com/about_wood/choosing-wood/from-log-to-plank/

	Softwood (C14-40)	Hardwood (D30-70)
Dimensions	140x140 to 394x394 to a length of max 9.1m	
Typical use	Post & beam construction	
Lamination	none	
Bending strength	14 - 50 N/mm²	30 - 70 N/mm²
Density	350 - 550 kg/m³	640 - 1080 kg/m³
Compression strength parallel	5.2 - 8.7 N/mm²	8.1 - 23 N/mm²
Compression strength perpendicular	2.1 - 3 N/mm²	2.2 - 4.6 N/mm²
Tension parellel	2.5 - 7.8 N/mm²	7.8 -13.8 N/mm²
Shear	0.6 - 1.4 N/mm²	1.4 - 2.6 N/mm²
E-modulus	6800 - 14500 N/mm²	9500 - 21000 N/mm²

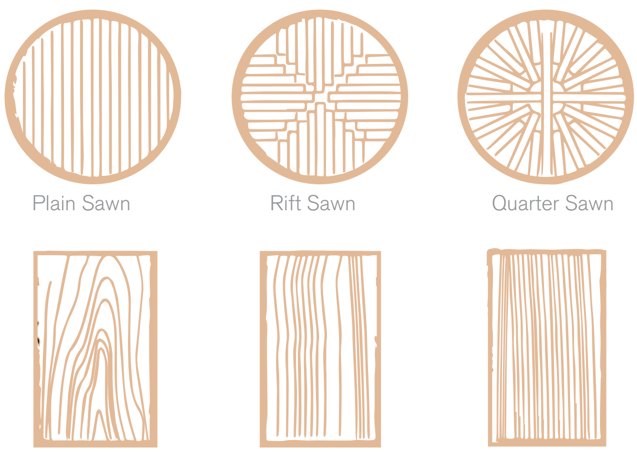
Heavy sawn timber or lumber beams (Harrop - Procter Forest Products)



The process from log to lumber (Swedishwood)



Common applications of sawn timber in mass timber structures are beams, columns and trusses.



Different methods of sawing produce different boards with different properties. Flat sawn is the most economical, but has the most variety in grain. This can cause the timber to warp or split. Quartersawn has straight grains and is very stable. Rift sawn is somewhere in between and inferior to quartersawn, but not as bad as plainsawn (Nicholson, 2013).

The Sakyamuna Pagoda of the Fogong Temple in Yingxian, China (Speck, 2019)

Stadshoutpaviljoen in Amsterdam by Florian Eckhart (Florian, 2016)

Glued Laminated Timber (Glulam)

Glue-laminated timber, also known as glulam, is a strucutral engineered wood element used for beams and columns. Glulam is stronger than steel at comparable weight and is stronger, stiffer, and more reliable than normal sawn lumber. The strength of the glulam is determined by the species of wood used and by the lamination.

Glulam can be made in different configurations. The standard configuration is horizontally stacked boards, but wide configurations are possible by laminating staggered stacks. Vertically laminations are also a possibility. Laminations are typically 33 to 35mm thick. The grains are always parallel to the length of the element (Thinkwood).

Glulam can either be homogenous, where all the laminations are of the same strength class, or combined, where the outer laminations are of higher strength than the inner ones (Ong, 2015). Because the boards can be laminated, lengths of up to 50m are possible, but transportation limitations should be considered.

Anthony Forest Products Company LLC. (2019). 2400F Stock Glulam. Retrieved from http://www.anthonyforest.com/ewp/2400f.shtml

Lightwood. Glulam. Retrieved from https://lightwood.org/products/glulam/

Ong, C. B. (2015). 7 - Glue-laminated timber (Glulam). In Martin P. Ansell (Ed.), *Wood Composites* (pp. 123-140): Woodhead Publishing.

Shigeru Ban Architects. (2010). Heasley Nine Bridges Golf Club House - Korea. Retrieved from http://www.shigerubanarchitects.com/works/2010_haesley-nine-bridges/index.html

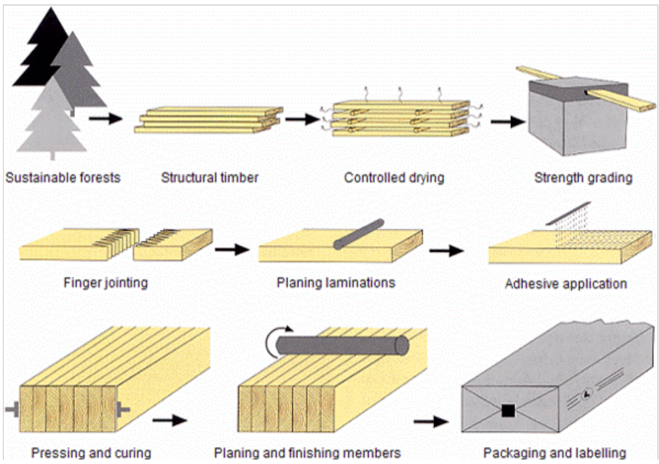
Skalko, D. (2014). Shigeru Ban's Aspen Art Museum opens. Retrieved from https://www.dezeen.com/2014/08/06/shigeru-ban-aspen-art-museum-opens/

Structural Timber Association. Glued laminated timber structures. *Structural Timber Engineering Bulletin*. Retrieved from http://www.structuraltimber.co.uk/assets/InformationCentre/eb8.pdf

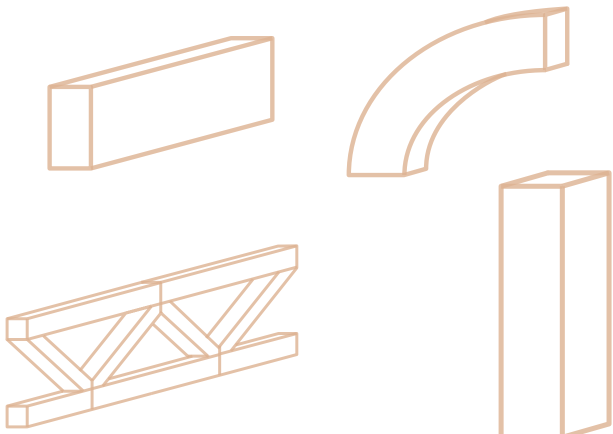
Thinkwood. Glue-Laminated Timber (Glulam). Retrieved from https://www.thinkwood.com/products-and-systems/mass-timber/glue-laminated-timber-glulam

Softwoods	GL c (combined)	GL h (homogeneous)
Dimensions	60 - 280mm x up to 1280 mm (typical, can be custom) length up to 18m typical, longer possible (transportation is the limiting factor)	
Typical use	Post & beam construction, arches, trusses	
Lamination	Glue lamined	
Bending strength	24 - 32 N/mm²	
Density	365 - 400 kg/m³	340 - 440 kg/m³
Compression strength	21.5 - 24.5 N/mm²	20 - 32 N/mm²
Tensile strength	17 -19.5 N/mm²	16 - 25,6 N/mm²
Shear	3.5 N/mm²	
E-modulus	8400 - 14200 N/mm²	8400- 14200 N/mm²

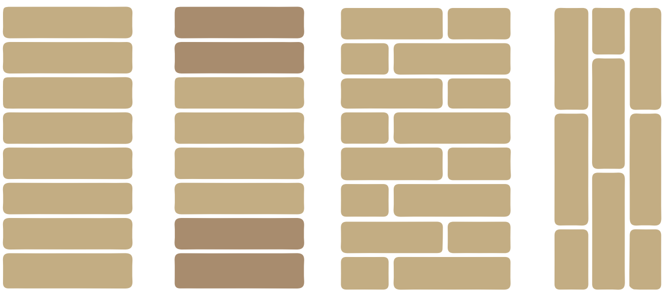
Glulam beams (Anthony Forest Products Company LLC, 2019)



Production process of glulam (Lightwood)



Common applications for glulam are beams, columns, arched beams or columns and trusses



Glulam can be extended in length using fingerjointing. It can also be made in different configurations and different shapes. Regular beams are laminated horizontally and can be made homogenous (Gl-h) or combined from different strengths (Gl-c) with the strongest grade on the edges. Beams wider than normally available can be made by laying boards of different widths side by side with overlap. If a tight curvature is required, the vertically laminated lay-out can be used (Structural Timber Association)

Aspen Art Museum by Shigeru Ban Architects (Skalko, 2014)

Nine Bridges Country Club by Shigeru Ban Architects (Shigeru Ban Architects, 2010)

Cross Laminated Timber (CLT)

Cross laminated timber, also know as CLT, is made from timber boards which are stacked crosswise and glued together. These consist usually of three, five or seven layers (FPinnovations & Binational Softwood Lumber Council, 2013). The panels can be manufactured at any dimension, however transportation restricts the total length. The strength of the CLT panel is determined by the wood species used, in general softwoods are used (Franke, 2016).

CLT can be made in different configurations for different uses. The thickness and build up of the panels can be adjusted, a thicker panel gives more strength. The more boards are in the direction of the main span, the better it can resist the forces acting upon it.

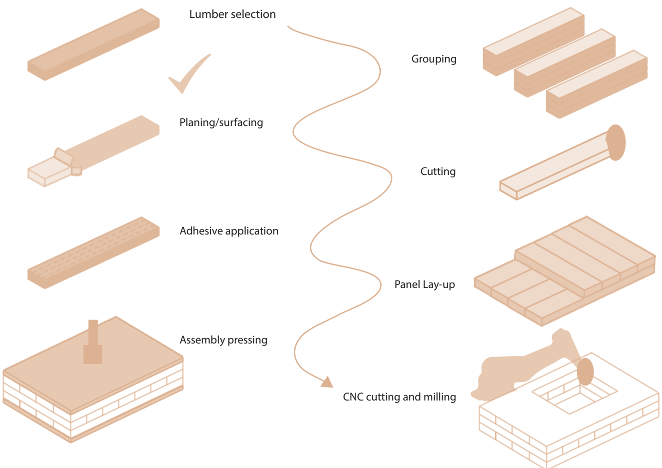
Because CLT is manufactured in panels it is mainly used in walls, floors and roofs. The main advantage of CLT compared to other timber products is its high shear strength. Additionally the panels can be CNC-milled at the factory, allowing for custom shapes and high precision.

FPinnovations, & Binational Softwood Lumber Council. (2013). CLT handbook - USA edition. Retrieved from Pointe-Claire:
Franke, Steffen. (2016). *Mechanical properties of beech CLT.*
Harris, T. (2015). Lakefront Kiosk / Ultramoderne. Retrieved from https://www.archdaily.com/778301/lakefront-kiosk-ultramoderne/5661ab6ae58ece70b60004ae-lakefront-kiosk-ultramoderne-photo
Natural Resources Canada. (2019). CLT panels waiting to be installed. Retrieved from https://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/forest/cross_laminated_timber_750.jpg
Peter, A. (2014). Wood Innovatio Design Centre / Micheal Green. Retrieved from https://www.archdaily.com/630264/wood-innovation-design-centre-michael-green-architecture/555214bfe58ece92c700026e-wood-innovation-design-centre-michael-green-architecture-photo
Schickhofer, Gerhard, Brandner, Reinhard, & Bauer, Helene. (2016). *Introduction to CLT, Product Properties, Strength Classes.*
Struiksma, A.F., Smilde, J.A., & van Houten, R.S. (2014). *Wood Would Mass timber as a sustainable substitute for traditional building materials.* (Master), University of Technology Delft, Delft.

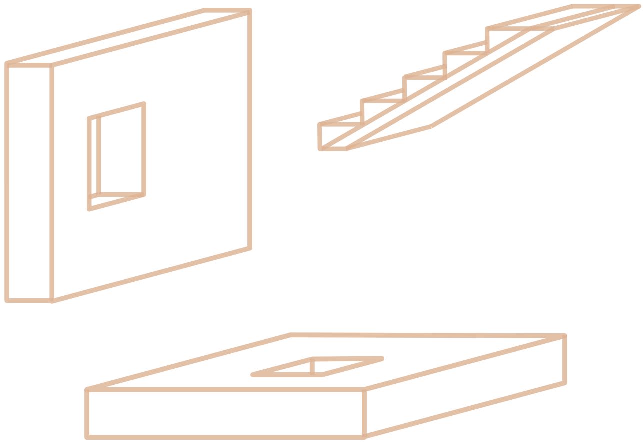
	CL 24h	CL 28h
Dimensions	Up to: 2.95 x 16.5m, thickness 0.5m	
Typical use	Walls, floors and roofs	
Lamination	Glue laminated	
Bending strength	24 N/mm²	28 N/mm²
Density	420 kg/m³	425 kg/m³
Compression strength parallel	24 N/mm²	28 N/mm²
Compression strength perpendicular	3 N/mm²	
Tension parallel	16 N/mm²	18 N/mm²
Shear	5.5 N/mm²	
E-modulus	11500 N/mm²	12600 N/mm²

Note: higher strengths can be achieved by using stronger wood species (Franke, 2016; Schickhofer, Brandner, & Bauer, 2016)

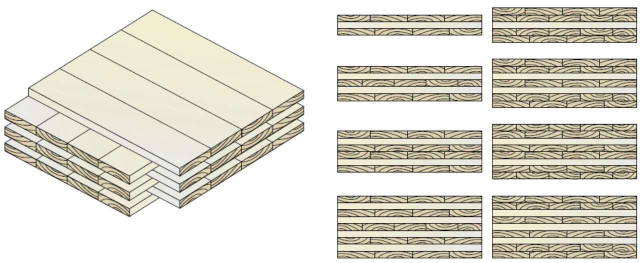
Cross laminated timber panels (Natural Resources Canada, 2019)



The production process of cross laminated timber after drying (Struiksma, Smilde, & van Houten, 2014)



Common applications for CLT are planar products such as walls, roofs and stairs



On the left the board lay-out for a cross laminated timber panel. On the right the different configurations for the panels. The top and bottom layer are always in the same direction and are parallel to the main span. On the right column of this picture, more boards are in direction of the span to increase the strength compared to the left column, which is more suitable for a two directional span (FPinnovations & Binational Softwood Lumber Council, 2013, p4)

Wood innovation and design centre by Michael Green in British Columbia (Peter, 2014)

Lakefront Kiosk by Yasmin Vobis and Aaron Forrest in Chicago (Harris, 2015)

Nail Laminated Timber (NLT)

Nail laminated timber, also known as NLT, is part of the mass timber panel family. It consists of lumber boards which are mechanically laminated using nails to create a solid element, in contrast with the glue used in glulam and similar products. Typical dimension lumber is used for the laminations. NLT can also be produced in a cross laminated fashion, comparable to CLT which is known as NCLT (nail cross laminated timber).

NLT is used for floors and roofs, but the panels can also be used for walls, elevator shafts and stair shafts. Plywood or OSB boards can be nailed to the face of the panel to provide in plane shear capacity, in this way it can be used as a shear wall or diaphragm (Binational Softwood Lumber Council & Forestry Innovation Investment Ltd., 2017). NLT is more efficient for one way spans than CLT because all fibers are oriented in the direction of the span.

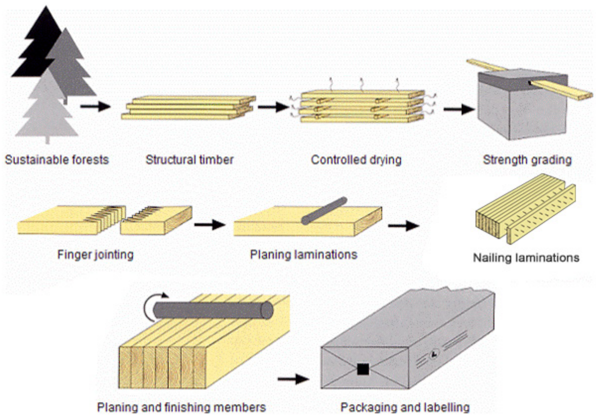
Exposed NLT panels are commonly used in ceilings for their architectural value as the boards have a distinctive finish, which can also be influenced by the dimensions of the boards creating an alternating pattern. The finish of the edges of the laminations also effects the aesthetics. NLT can also be produced in curved panels in the main span direction.

Binational Softwood Lumber Council, & Forestry Innovation Investment Ltd. (2017). Nail Laminated Timber Canadian Design & Construction Guide V1.1. Retrieved from
Dialog Architects. (2015). The old is new again with Nail Laminated Timber. Retrieved from https://www.treehugger.com/green-architecture/old-new-again-nail-laminated-timber.html
Peter, E. (2016). America's largest modern timber building pieces together like lego. https://inhabitat.com/americas-largest-modern-timber-building-pieces-together-like-lego/
ThinkWood. (2017). Selecting Lumber for Making NLT. Retrieved from https://www.thinkwood.com/news/selecting-lumber-making-nlt

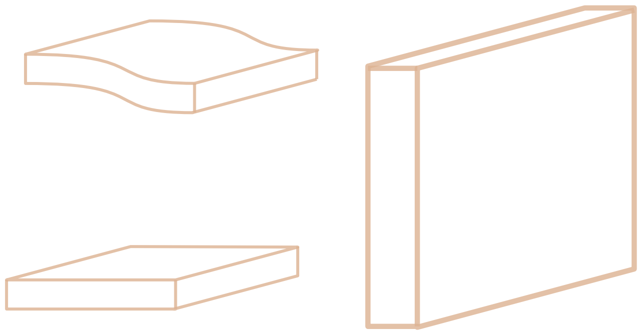
Dimensions	Depth: 89, 140, 184, 235, 286, 314mm, width up to 3.6m, length up to 30m
Typical use	Floors, ceilings, walls
Lamination	Mechanically by nails
Bending strength	16 N/mm²
Density	420 kg/m³ (depends on wood species)
E-modulus	14000 N/mm²

Note: properties depend on manufacturer and wood species

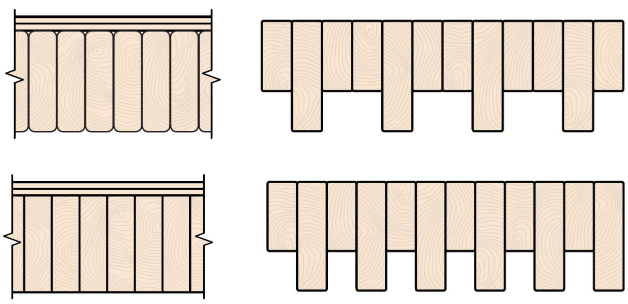
Nail laminated timber (ThinkWood, 2017)



The production process of nail laminated timber



Common applications for NLT are ceilings, walls and floors. The boards can also be aligned to form curved elements



Different build ups for NLT panels. The finishing of the timber can have an influence on the aesthetics of the panel (kerf, chamfer, eased or square edge). Different sizes of boards can also be used for a staggered finish. NLT can also be used in combination with timber boards to strengthen in plane loading (Binational Softwood Lumber Council & Forestry Innovation Investment Ltd., 2017)

T3 in Minneapolis by Michael Green Architecture (Peter, 2016)

Chilliwack Secondary School by Dialog Architects(Dialog Architects, 2015)

Dowel Laminated Timber (DLT)

Dowel laminated timber, also known as DLT or Brettstapel, is an all timber panel, meaning it does not contain glue or other materials for lamination. Different species of wood have different expansion rates under different moisture conditions. DLT makes use of this property by inserting hardwood dowels into softwood lumber, the dowels expand more than the surrounding wood and the boards are then laminated with the friction force.

DLT in its traditional form performs similar to glulam and NLT. The grains of the boards run parallel to the span, making it more efficient than CLT. DLT is also stronger than NLT as the dowels hold each board side by side. DLT can also be easily milled or routed compared to NLT as it does not contain nails. The dowels can also be inserted diagonally instead of perpendicular to offer additional resistance (Thinkwood).

DLT can have the same type of finishings as NLT. A new development is the cross laminated version, with the notable product of Nurholz by Rombach. The product uses threaded dowels to create a strong connection and in combination with board layers and cross lamination a solid panel can be created which is also strong for in plane loading (Rombach).

Epp, L. (2018). A new mass timber product in North America. Retrieved from http://www.wooddesignandbuilding.com/dowel-laminated-timber/

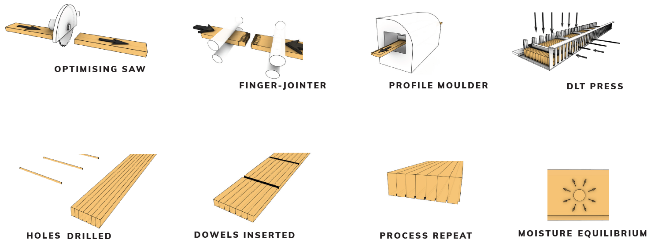
Rombach. *Nur-Holz Die Einstoffliche Massivolz-Bauweise aus dem Schwarzwald Planungsbroschure.* Retrieved from https://www.nur-holz.com/fileadmin/user_upload/aktuelles/Download/NUR-HOLZ_Planungsbroschuere_1._Aufl._UEberarb._Feb_2019_-zum_Versand.pdf

StructureCraft. Dowel Laminated Timber - A North American First. Retrieved from https://structurecraft.com/projects/museum-of-fine-arts-houston

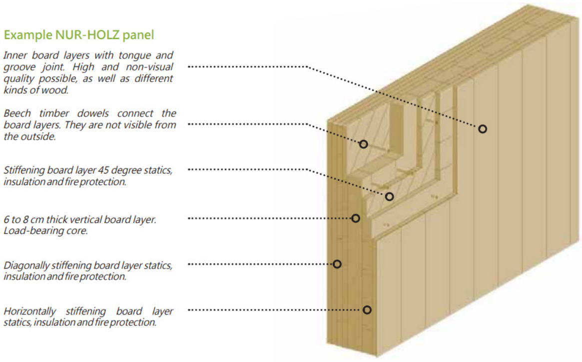
StructureCraft. Western Yacht Harbor Office. Retrieved from https://structurecraft.com/projects/western-yacht-harbor

StructureCraft. (2019). *Dowel Laminated Timber The All Wood Mass Timber Panel.*

Thinkwood. Dowel-Laminated Timber (DLT). Retrieved from https://www.thinkwood.com/products-and-systems/mass-timber/dowel-laminated-timber-dlt



The production process of dowel laminated timber (StructureCraft, 2019)

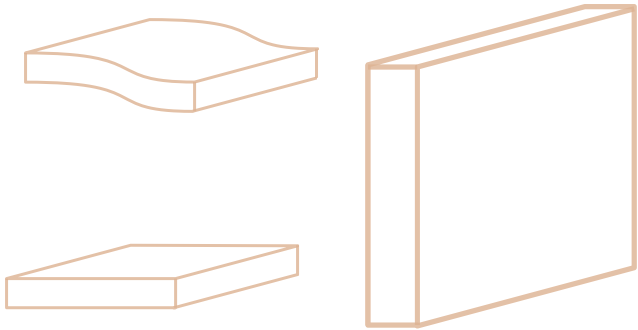


Next to the traditional panel build up, the company Rombach engineered a cross laminated variation using beech threaded dowels to connect the boards together. The panels can span floors of up to 8m with 25cm thickness. For a live load of 6 kN/m[2] the panels can span 6m (Rombach).

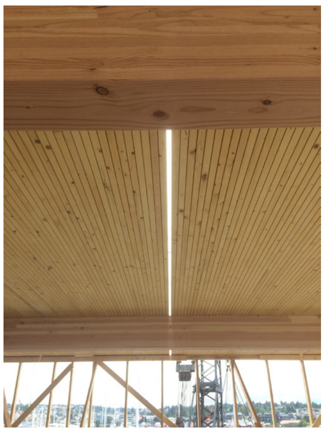
Dimensions	Depth: 89, 140, 184, 235, 286, 314mm, width up to 3.6m, length up to 30m
Typical use	Floors, ceilings, walls
Lamination	Mechanically by dowels
Bending strength	16 N/mm²
Density	420 kg/m³ (depends on wood species)
E-modulus	14000 N/mm²

Note: properties depend on manufacturer and wood species

Dowel laminated timber (Epp, 2018)



Common applications for DLT are walls, floors, roofs and ceilings.



Western Yacht Harbor in Seattle by Patana Studio Architecture (StructureCraft)

Museum of Fine Arts in Houston by Lake Flato Architects (StructureCraft)

Laminated Veneer Lumber (LVL)

Laminated veneer lumber, also known as LVL, is made from laminating multiple veneers on top of each other. The veneers are obtained from logs by peeling them using a lathe. By doing so, all natural defects such as knots, slope of grain and splits are dispersed throughout the material (Canadian Wood Council, 2019). The result is a predictable uniform product, with rougly 1.3 times the strength of glulam and 2 times the strength of sawn timber. It is also twice as strong as steel proportionate to weight (Stora Enso).

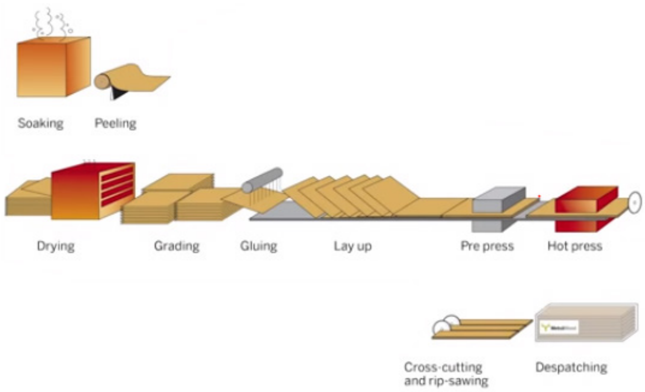
LVL is mainly used for columns and for beams, but it can also be produced in panels. Due to the nature of fabrication, it is also highly suitable for curved designs. LVL can also be used as an addition to other timber products to provide more strength in specific areas. The LVL products can also be precisely milled using CNC routers in the factory.

Canadian Wood Council. (2019). Laminated Veneer Lumber (LVL). Retrieved from http://cwc.ca/how-to-build-with-wood/wood-products/structural-composite/laminate-veneer-lumber/
David, F. Ultralam Taleon Terra. Retrieved from https://www.universalply.com/brands/ultralam/
Grassi, A. (2016). One Main. Retrieved from http://www.decoi-architects.org/2011/10/onemain/
Metsä Group. (2015). Metsä Wood KERTO® laminated veneer lumber (LVL) – production video.
Pollmeier Massivholz GmbH & Co.KG. (2019). About Baubuche. Retrieved from https://www.pollmeier.com/en_US/Products/baubuche/baubuche-about.html#gref
Södra Wood. UltralamTM R LVL Beams. In Södra (Ed.). Cirencester.
Stora Enso. Wonder of wood - Pushing beyond wood's percieved boundaries. Retrieved from https://www.storaenso.com/en/products/wood-products/massive-wood-construction/lvl
Ultralam. LVL Ultralam. Retrieved from https://ultralam.com/products/laminated-veneer-lumber-lvl/

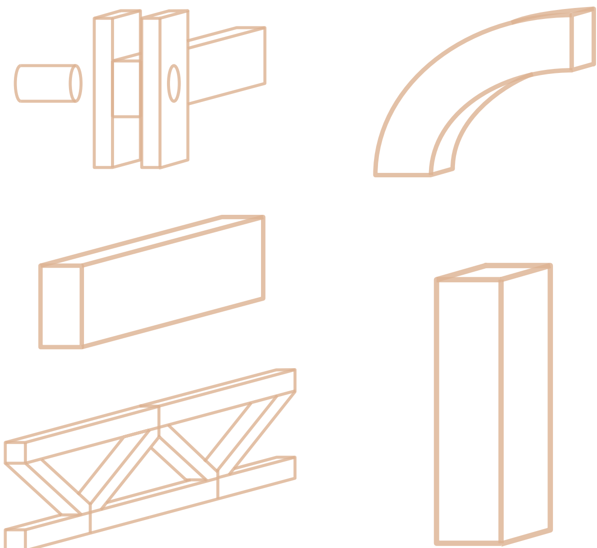
Dimensions	up to 280mm thick, 600mm wide, 24m long	
Typical use	Columns, beams, edge material	
Lamination	Glue laminated	
Bending strength	48 N/mm²	
Density	480 kg/m³	
Compression strength	Parallel to grain	40 N/mm²
	Perp. To grain edgewise	7.5 N/mm²
	Perp. To grain flatwise	3.8 N/mm²
Tension	Parallel to grain	36 N/mm²
	Perpendicular to grain	0.9 N/mm²
Shear	Edgewise	4.6 N/mm²
	Flatwise	3.2 N/mm²
E-modulus	14000 N/mm²	

Note: mechanical properties of LVL are dependent of the manufacturer, these properties are taken from Ultralam (Södra Wood). Higher strength can be obtained witht he use of hardwood such as beech (Pollmeier Massivholz GmbH & Co.KG, 2019)

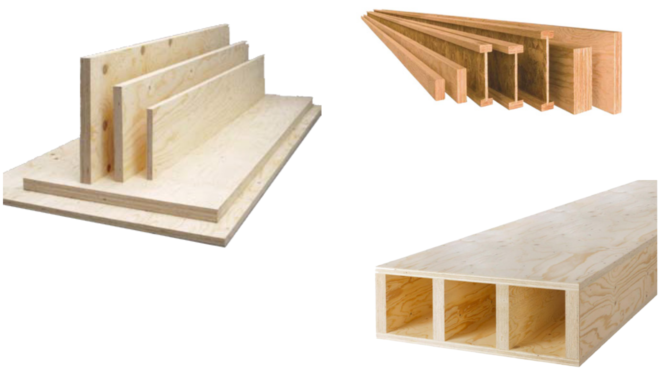
Laminated veneer lumber panels (Ultralam)



The production process of laminated veneer lumber (Metsä Group, 2015)



LVL has many applications, most common are beams and columns. It also lends itself for curved columns and beams. The strong properties also make it ideal for high strength applications, such as in connections



Next to traditional applications of columns and beams, LVL can also be produced in panels. These panels can be combined with other timber products to form composite elements, such as I beams, or be used to create other shapes, such as a hollowcore timber floorpanel.

The Metropol Parasol in Sevilla by Jurgen Mayer (David)

One Main office in Boston by dECOi Architects (Grassi, 2016)

Parallel Strand Lumber (PSL)

Parallel Strand Lumber, or PSL, has high strength, stiffness and dimensional stability compared to regular sawn timber. It is made from flaked wood strands (either from 'waste' from LVL production or produced specifically for PSL) that are arranged parallel on the longitudinal axis, with a length to thickness ratio of approximately 300. The strands are formed into a billet and pressed and cured together using microwave radiation (Canadian Wood Council, 2019).

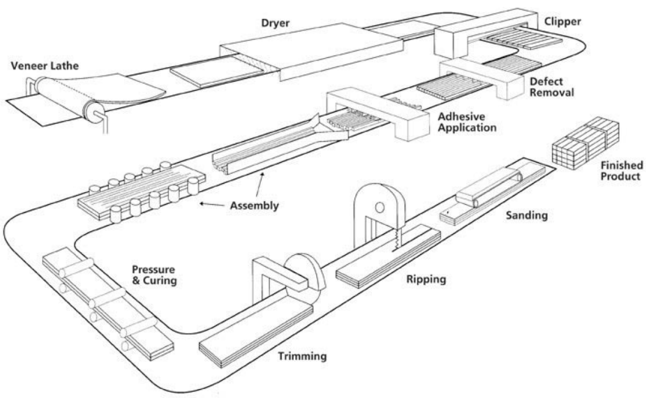
PSL is stronger and stiffer than LSL and also has a higher fiber utilization than LVL. It can be easily bolted and is in general used for columns, headers, beams and trusses (Landreman, 2012). The manufacturing process makes it possible to create large members from relatively small trees. It is also possible to create custom shapes.

American Wood Council. *Structural Composite Lumber & Glued Laminated Tiber Awareness Guide.* Retrieved from Leesburg: https://www.woodaware.info/pdf/glulam-scl.pdf
Canadian Wood Council. (2019). Parallel Strand Lumber (PSL). Retrieved from http://cwc.ca/how-to-build-with-wood/wood-products/structural-composite/parallel-strand-lumber/
Lam, Frank. (2001). Modern structural wood products. *Progress in Structural Engineering and Materials*, 3(3), 238-245. doi:10.1002/pse.79
Landreman, A. (2012). Retrieved from http://www.woodworks.org/wp-content/uploads/2013-WS-Mar-Landreman.pdf
StructureCraft. Parallel Strand Lumber. Retrieved from https://structurecraft.com/materials/engineered-wood/parallel-strand-lumber
StructureCraft. (2006). Bamfield Marine Centre Roof.
Tomasulo, K. (2017). Exposed Engineered Wood Completes Modern Bran House Interior.
Weyerhaeuser. Parallam PSL Beams turn open floor plans into reality. Retrieved from https://www.weyerhaeuser.com/woodproducts/engineered-lumber/parallam-psl/parallam-psl-beams/

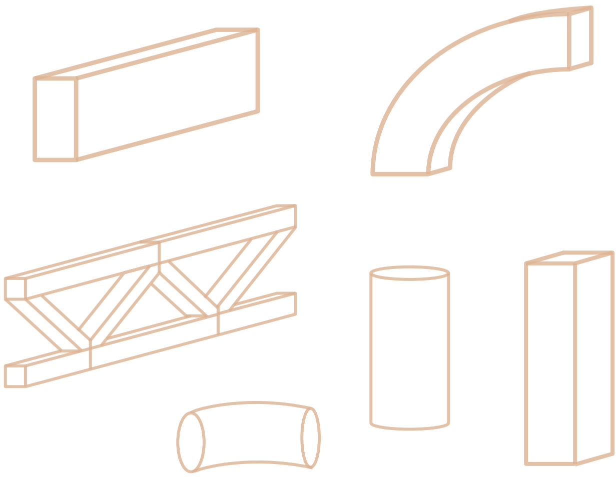
Dimensions	Typical beams: 68,89,133,178 x max 457mm Typical columns: square 89, 133, 178mm	
Typical use	Columns, beams, headers, trusses	
Lamination	Glue laminated and cured using microwaves	
Bending strength	37 N/mm^2	
Density	720 kg/m^3	
Compression strength	Parallel to grain	32 N/mm^2
Tension	Parallel to grain	10 N/mm^2
Shear		3.7 N/mm^2
E-modulus	15000 N/mm^2	

Note: mechanical properties of PSL are dependent of the manufacturer, these properties are taken from Parallam (Lam, 2001)

Parallel strand lumber beams (Weyerhaeuser)



The production process of parallel strand lumber (American Wood Council)



Applications for PSL as mass timber can be in any shape or form for beams, columns and trusses

PSL can be manufactured in many shapes and used in different applications. These are some examples in combination with steel intermediary connections or steel composite beams (StructureCraft)

The Bamfield Marine Centre Roof in Bamfield, British Columbia (StructureCraft, 2006)

Modern Green Barn by Stott Achitecture in Sagaponack, New York (Tomasulo, 2017)

Plywood

Plywood is a wooden panel made out of cross laminated veneers, so each layer of grain is perpendicular to the other. A plywood panel is composed out of at least 3 veneers. Birch is typically made of spruce, although birch is used for higher strength or a hard surface. The veneers are made by peeling a log with a lathe. The veneers are dried and then glued and pressed together to form a panel (UPM, 2019).

Plywood is dimensionally stable, is strong in two directions and has excellent stiffness and strength to weight ratio. The panels can be CNC-machined or simply cut to the standard dimensions. Coatings need to be applied to protect the material from weather and impact. Plywood can be used as exterior cladding or roof sheating. They can also perform structurally providing lateral resitance (Canadian Wood Council, 2019).

Ashley Timber Ltd. (2019). Birch Plywood 9mm BB/BB faced 2440x1220. Retrieved from https://www.ashleytimber.co.uk/product/birch-plywood-9mm-bb-bb-faced-2440x1220mm/

Canadian Wood Council. (2019). Plywood. Retrieved from http://cwc.ca/how-to-build-with-wood/wood-products/panel-products/plywood/

Clancy, A. (2015). Scale of PLY. Retrieved from https://www.archdaily.com/593873/scale-of-ply-noji-architects/54d024d4e58ece5c5e000403-6bt-1155_2880-jpg

Freres, T. (2019). Mass Plywood Product Passes Two Milestones. Retrieved from https://frereslumber.com/2019/02/mass-plywood-product-passes-two-milestones/

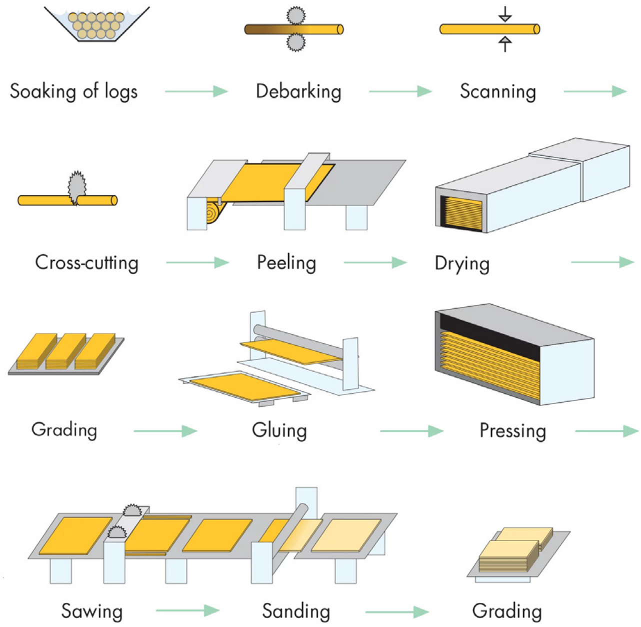
Say, A. (2018). Twist by Emtech. Retrieved from https://parametric-architecture.com/twist-by-emtech/

UPM. (2019). About Plywood. Retrieved from https://www.wisaplywood.com/products/about-plywood/

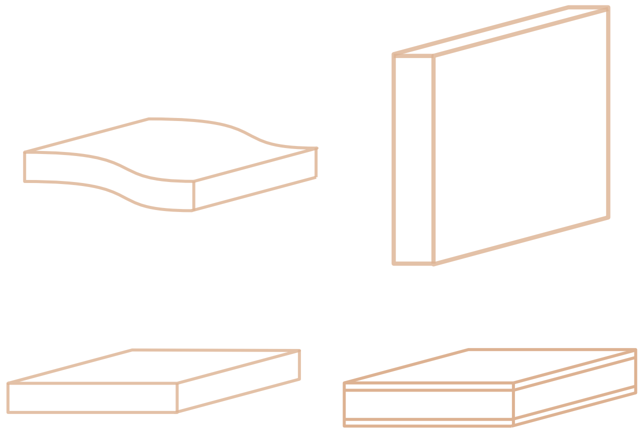
Dimensions	Thickness: up to 28.5mm Width: 1220 mm Length: up to 3050mm
Typical use	Sheathing
Lamination	Glue
Bending strength	48 N/mm²
Density	600 kg/m³
Compression strength	34 N/mm²
Tensile strength	28 N/mm²
Shear strength	7 N/mm²
E-modulus	13100 N/mm²

Note: properties depend on manufacturer and wood species

Plywood (Ashley Timber Ltd., 2019)



The production process of plywood (UPM, 2019)



Plywood can be used as a panel to strengthen other mass timber products such as DLT and NLT but can also be used in itself for walls, floors and ceilings.

Mass plywood panels are a new mass timber product, consisting of numerous crosswise layered veneer glued together. It is basicly a wide LVL beam. The disadvantage compared to CLT is that it uses more glue, the advantage is that more timber can be used from a log due to the peeling process (Freres, 2019).

Scale of PLY by NOJI architects in Dublin, Ireland (Clancy, 2015)

TWISTed Plywood by Emtech at the Timber Expo in Birmingham (Say, 2018)

Laminated Strand Lumber (LSL)

Laminated strand lumber, or LSL, is comparable to PSL except it is made from smaller strands. Two types can be distinguished, boards or panels where the strands are all aligned in the direction of the major axis, or boards where a portion of the strands is orientated to the minor axis. In general the strands used are from waste materials or pieces that are too small, weak or misshapen for other uses (Graham).

In the production process the strands are dried and orientated for maximum strength. They are glued and pressed together using a steam injection process. Because of the nature of the material, LSL offers good connection strength and ductility. It is not prone to splitting failuers such as sawn timber or glulam (StructureCraft).

American Wood Council. *Structural Composite Lumber & Glued Laminated Tiber Awareness Guide.* Retrieved from Leesburg: https://www.woodaware.info/pdf/glulam-scl.pdf

Graham, S. Why Use Laminated Strand Lumber.

StructureCraft. Laminated Strand Lumber. Retrieved from https://structurecraft.com/materials/engineered-wood/laminated-strand-lumber

StructureCraft. LSL panels.

StructureCraft. (2010). SAIT Parkade Skylight. Retrieved from https://structurecraft.com/projects/sait-parkade-skylight

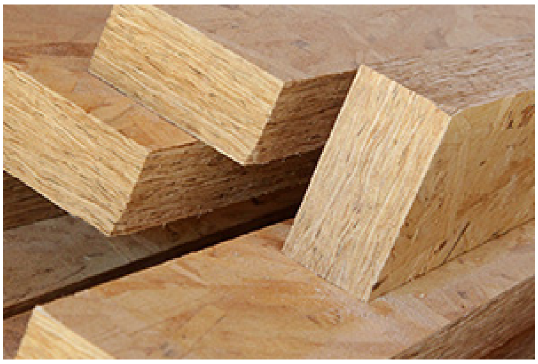
StructureCraft. (2014). North Vancouver City Hall.

The Engineered Wood Association. (2016). *Structural Composite Lumber (SCL) Making the best use of resources.* Retrieved from https://www.apawood.org/structural-composite-lumber

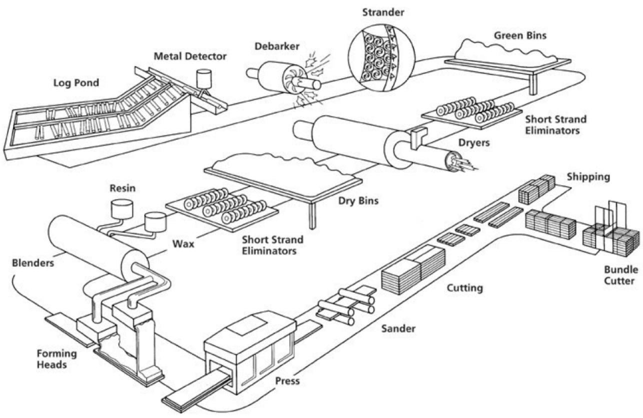
Weyerhaeuyser. Timberstrand LSL Floor Joists: for floor performance and code requirements. Retrieved from https://www.weyerhaeuser.com/woodproducts/engineered-lumber/timberstrand-lsl/timberstrand-lsl-framing-lumber/timberstrand-lsl-floor-joists/

Dimensions	Typical beams: 68,89,133,178 x max 457mm Typical columns: square 89, 133, 178mm	
Typical use	Columns, beams, headers, trusses	
Lamination	Glue laminated	
Bending strength		39 N/mm²
Density		550 kg/m³
Compression strength	Parallel to grain	15 N/mm²
Tension	Parallel to grain	9 N/mm²
Shear		9 N/mm²
E-modulus		10600 N/mm²

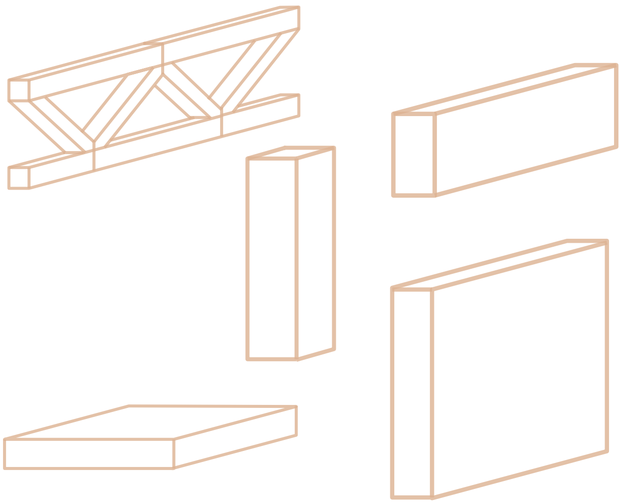
Note: mechanical properties of LSL are dependent of the manufacturer



Laminated strand lumber product (The Engineered Wood Association, 2016)



The production process of laminated strand lumber (American Wood Council)



LSL can be used in beams and columns, but also be produced in large panels which can be custum milled into any shape

Application of LSL in traditional joists and frame construction at the top (Weyerhaeuyser) and LSL mass timber panels at the bottom (StructureCraft).

The SAIT Parkade Skylight by Bing Thom Architects in Calgary, Alberta (StructureCraft, 2010)

North Vancouver City Hall, featuring mass timber LSL panels, by MGA Architects in Vancouver, Canada. (StructureCraft, 2014)

Oriented Strand Board (OSB)

Oriented strand board, or OSB, is a wood panel made out of strands. The strands are arranged in cross-oriented layers and glued and pressed together. It is simular to plywood in performance and characteristics. Because of the manufacturing method OSB is a dimensionally stable panel that resists deflection, delaminiation and warping (The Engineered Wood Assoiciation, 2019). It is produced in large mats of consistent quality which are sawn into standard or custom dimensions.

OSB is commonly used as a sheathing material for flooring, subflooring, wall sheathing, roof sheathing or ceiling sheathing. It can also be combined with joists to create insulated panels. OSB is also used for the web in a combined timber I-beam.

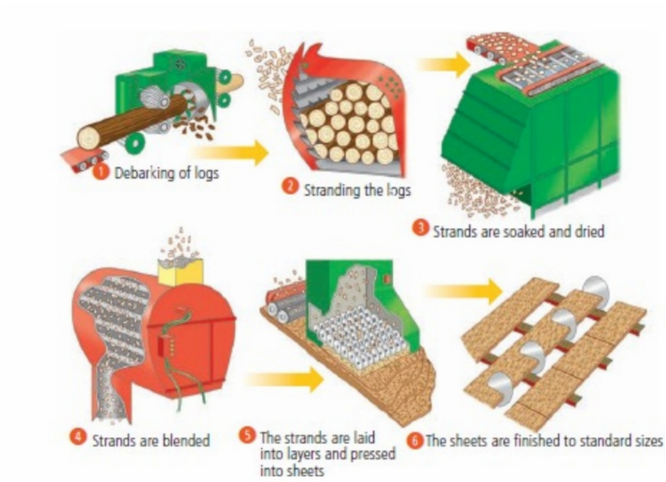
(The Engineered Wood Assoiciation, 2019)

Cross, M. (2019). Wood materials technology. Retrieved from https://www.slideshare.net/MrWoodwork/15-manufactured-boards
H&M Timber Ghana Limited. (2018). Uses of OSB. Retrieved from https://hmtimberghana.com/osb/
Hiziroglu, S. (2017). Oriented Strand Board as a Building Material. Retrieved from http://factsheets.okstate.edu/documents/fapc-145-oriented-strand-board-as-a-building-material/
Kronospan. (2019). Kronospan Oriented Strand Board (OSB). Retrieved from https://www.universalply.com/product/osb-oriented-strand-board/
Stevens, P. (2017). Cloudflare's first UK office is organized around an inhabitable OSB structure. Retrieved from https://www.designboom.com/architecture/cloudflare-first-uk-office-jump-studios-london-interiors-01-30-2017/
The Engineered Wood Assoiciation. (2019). Oriented Strand Board (OSB) Versatile panel with consistent quality. Retrieved from https://www.apawood.org/osb

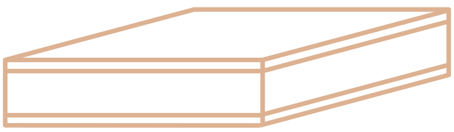
Dimensions	Thickness: up to 28.5mm Width: 1220 mm Length: up to 3050mm
Typical use	Sheathing
Lamination	Glue
Bending strength	28 N/mm²
Density	600 kg/m³
Compression strength	17 N/mm²
Tensile strength	10 N/mm²
Shear strength	10 N/mm²
E-modulus	8200 N/mm²

Note: properties depend on manufacturer and wood species

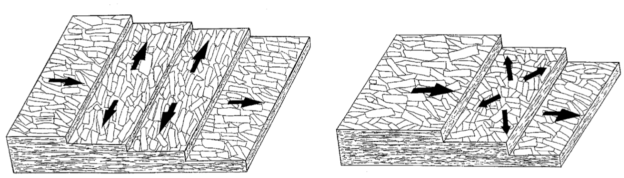
Oriented strand board (Kronospan, 2019)



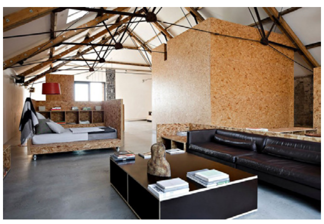
The production process of oriented strand board (Cross, 2019)



OSB is not a mass timber product on itself. It can however be added to other mass timber products for added strength for in plane loading



Schematic drawing of different build ups for oriented strand boards. On the left the strands are oriented on two axis, the outer layers in the same direction and the centre layers in the other direction. On the right the strands on the outer layers are oriented on the same axis, the centre layer is in all directions (Hiziroglu, 2017).



OSB is often used for sheathing (H&M Timber Ghana Limited, 2018)

OSB in interior design for an office by Jump Studios (Stevens, 2017)