Dominik Auclair

Comparison of Fasteners and Joining Techniques in Modular Timber Construction

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Wilhelmshaven Oldenburg Elsfleth

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Foreword

This paper presents the thesis work conducted by Dominik Auclair from Jade UAS, Oldenburg, Germany. The work includes research findings from his internship work at Karelia UAS for the "Sustainable Building Technologies- Community of Practice" (SBTCP) project and further research in comparing different fasteners, joining techniques for modular timber construction. He was involved in activities such as background research work, as well as construction company and site visits during his internship; which eventually supported him to develop his bachelor thesis topic and research further.

The SBTCP project by Karelia UAS in collaboration with Salzburg UAS and Jade UAS aims to enhance the sustainable development of timber construction through using advanced expertise and technologies. The project has three fundamental pillars of research activities: 1) sustainable buildings, 2) material sciences, and 3) building information modelling. Dominik's bachelor thesis titled 'Comparison of Fasteners and Joining Techniques in Modular Timber Construction' addresses several important aspects of sustainability, circularity, and competitiveness of timber construction aligning with the key research areas of the project. His thesis literature review started during his internship work at Karelia UAS, resulting in his final thesis work.

Dominik's internship activities have been supervised by Prof. Sebastian Hollermann from Jade UAS, and Timo Pakarinen and Shammi Keya from Karelia UAS. His thesis work was supervised by Prof. Sebastian Hollermann from Jade UAS, and Timo Pakarinen from Karelia UAS.

This has been a successful collaboration activity supported by the SBTCP project and we look forward to continuing the cooperation between Karelia UAS and Jade UAS.

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Jade University of Applied Sciences Oldenburg

Faculty of Civil Engineering

Bachelor Thesis

Comparison of fasteners and joining techniques of modular timber construction

For obtaining the academic degree

Bachelor of Engineering (B. Eng.)

Submitted by: Auclair, Dominik

Matriculation No.: 6033137

Task

Jade Hochschule Wilhelmshaven/Oldenburg/Elsfleth

- [ ] Studiengang Angewandte Geodäsie
- [ ] Studiengang Assistive Technologien
- [ ] Studiengang Geoinformatik
- [x] Studiengang Bauingenieurwesen
- [ ] Studiengang Hörtechnik und Audiologie
- [ ] Studiengang Wirtschaftsingenieurwesen-Bauwirtschaft
- [ ] Studiengang Wirtschaftsingenieurwesen-Geoinformation

<u>Ausgabe einer Bachelor-Arbeit</u>

Für die Studierende/für den Studierenden

Auclair, Dominik	6033137
Name, Vorname	Matr.-Nr.

wird hiermit die **Bachelor-Arbeit mit dem nachstehenden Thema** ausgegeben:

Comparison of fasteners and joining techniques of modular timber construction

The aim of this research is to create a table that examines and compares different fasteners and connection techniques between individual timber modules for different requirements. For this purpose, manufacturer specifications, material properties, building physics and construction aspects are qualitatively evaluated so that the ideal connection option can be taken for each building type.

Deutsche Übersetzung des Themas der Bachelor-Arbeit:

Verbindungmittel und Verbindungtechniken von Holzmodulen im Vergleich

Das Ziel dieser Forschung ist es eine Tabelle zu erstellen, die unterschiedliche Verbindungsmittel und Verbindungstechniken zwischen einzelnen Holzmodulen auf verschiedene Anforderungen untersucht und vergleicht. Dafür werden Herstellerangaben, Materialeigenschaften, Bauphysikalische und Bautechnische Aspekte qualitativ ausgewertet, sodass für jeden Gebäudetyp die ideale Verbindungsmöglichkeit entnommen werden kann.

ErstprüferIn: Prof. Dr. -Ing. Sebastian Hollermann

ZweitprüferIn: Timo Pakarinen Lecturer Lic (For), MSc (Eng.), DI (FH) DI Hermann Huber

Die Arbeit wird ausgegeben als Einzelarbeit/~~Gruppenarbeit mit der/dem Studierenden~~

Sebastian Hollermann

Unterschrift ErstprüferIn

Ausgabetag:	16.12.2022
Bearbeitungszeit:	8 Wochen
Abgabetag:	10.02.2023
Verlängerungsantrag vom:	....
Verlängerung der Abgabefrist bis:	....
Arbeit abgegeben am:	10.02.2023

Die Bachelor-Arbeit ist in **zwei**facher Ausfertigung für die Studiengänge Angewandte Geodäsie, Bauingenieurwesen, Geoinformatik und Wirtschaftsingenieurwesen- Geoinformation, in **drei**facher Ausfertigung für den Studiengang Wirtschaftsingenieurwesen- Bauwirtschaft (PO 2010/2018) und für die Studiengänge Assistive Technologien und Hörtechnik und Audiologie in **vier**facher Ausfertigung und einer digitalen Version im Prüfungsamt innerhalb der Öffnungszeiten abzugeben. In den Studiengängen Bauingenieurwesen und Wirtschaftsingenieurwesen- Bauwirtschaft kann eine weitere digitale Version verlangt werden.

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In der Bachelor-Arbeit ist schriftlich zu versichern, dass die Bachelor-Arbeit - bei einer Gruppenarbeit der entsprechend gekennzeichnete Anteil der Arbeit - selbständig verfasst wurde und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt wurden (§ 21 Absatz 5 Teil A BPO).

Ich bestätige, das Thema der Bachelor-Arbeit am 16.12.2022 erhalten zu haben.

Dominik Auclair

Unterschrift Studierende/r

Foreword

This thesis was written to obtain a bachelor's degree in Civil Engineering specialising in modular timber construction at the Jade University of Oldenburg, Germany. The theme of this graduation thesis is the comparison of fasteners and connecting techniques in modular timber construction. As we live in a world that faces an immense climate change sustainable constructions are getting increasingly important. Also, due to the lack of qualified personnel, processes in construction industry need to be optimized to achieve an efficient way of creating new architecture. My participation in the scientific research project "Sustainable Building Technologies - Community in Practice" at the Karelia University of Joensuu, Finland in autumn 2022, influenced me to focus on a topic with a sustainable background in my bachelor thesis. As parts of this bachelor thesis can possibly be used for the scientific research project in Joensuu, I decided to write this paper in English to make it internationally accessible. Within this thesis I want to thank all my colleagues in Joensuu for their support, motivation and hospitality during my stay. Also, I am very grateful for the help that I received and want to thank all the companies and people that assisted me in writing this bachelor thesis.

Abstract

The aim of this bachelor thesis is to create a table that examines and compares different fasteners and connection techniques to join individual wooden modules depending on different requirements. For this purpose, manufacturer specifications, material properties, building physics and construction aspects are qualitatively evaluated, so that the ideal connection option can be found for each building type. For the processing of the task already used concepts were discussed with experts. Based on these discussions, results are presented and the properties of the fasteners are shown and compared in a table. Concerning the subject of connecting techniques for individual modular timber constructions, obtaining the needed information can be very challenging. The techniques, that are already developed, are traded internally and are not published, this is why it can be said, there is a lack of information in this sector. Only a few companies are willing to share their experience and know-how.

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List of abbreviations

CLT .... *Cross-laminated-timber*
CNC .... *Computerized Numerical Control*
db .... *Decible*
DIN .... *Deutsches Institut für Normungen*
EC5 .... *Eurocode 5*
EN .... *Europäische Norm*
HCW .... *Hilti Connector Wood*
NA .... *Nationaler Anhang*
OSB .... *Oriented-Strand-Board*

1 Introduction

The aim of this bachelor thesis is to investigate and compare fasteners and joining techniques for connecting individual modular timber construction. In the modern building industry modular timber constructions are increasingly used for buildings such as residential buildings, educational buildings, administration buildings and hospitals. Since each building is different, individual solutions are required to ensure the proper connection of modular timber construction. In order to provide a comparison of the fasteners and connection techniques, different parameters such as static properties, building physics and structural properties are taken into account. Furthermore, the fasteners and joining techniques are investigated based on material properties, manufacturer specifications and constructional aspects. The research is based on internet and reading sources, personal and e-mail conversations with experts and own experience.

The outcome of this bachelor thesis is a table, which enables professionals to verify whether a fastener or a joining technique can be used for a certain modular timber structure or not.

Even though modular timber construction is increasingly used, I expect it to be very difficult to do research on this topic, because there may be a lack of information in this area. This is due to the fact that companies do not want to publish construction details and solutions that they developed (Goetz, 2023).

Due to climate change and a change in the way people think, sustainable constructions are becoming crucial. Since wood is a sustainable raw material, which can be deconstructed and adapted, if used in a modular timber construction and therefore leads material savings, wood could be used as a sustainable building material.

The Corona pandemic, refugee crises and natural disasters have shown us, that sometimes specific buildings need to be erected quickly. By using modular timber construction, which are not only easy to produce but also easy to rearrange, residential buildings, hospitals and schools can be built in a short time.

The first part of this paper deals with the meaning of the term modular timber construction, how the modules are constructed and how they can differ. Afterwards, it is explained what loads have to be applied to the connection points between several modules. However, the main part of this bachelor thesis is to compare the fasteners and connection techniques. Therefore, fasteners, connection techniques and different comparison parameters are presented. This includes static properties without static calculation, structural properties, building physical properties and some other characteristics.

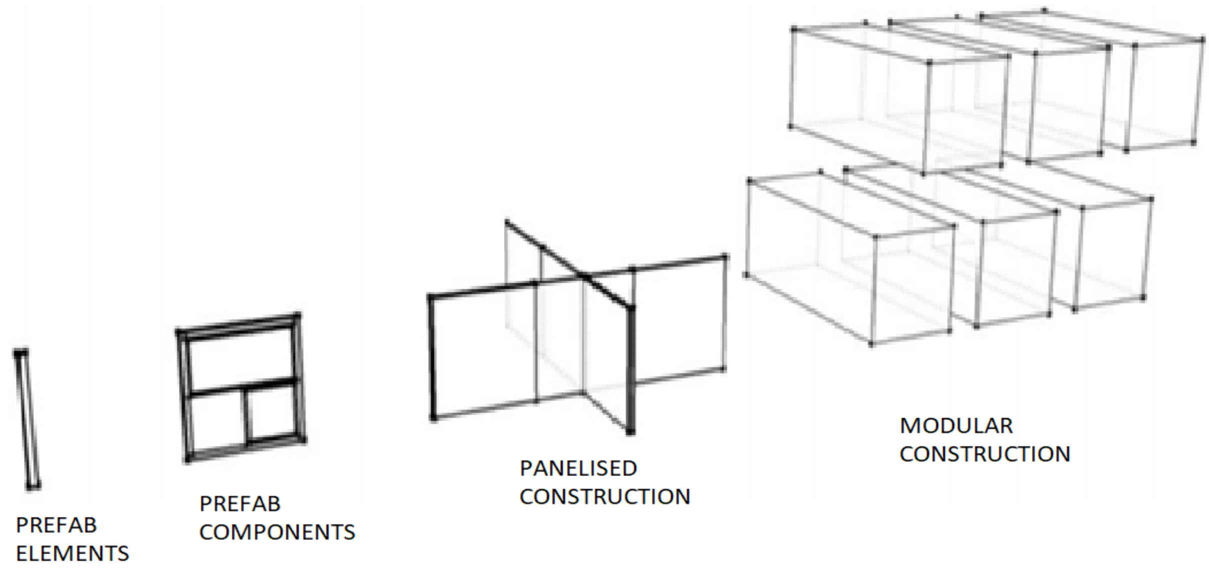
All figures, that are used in this bachelor thesis were created to give a brief insight into how connections, modular timber constructions or other structures can possibly be designed. In some special cases, when for example the building has a certain height, special solutions need to be found. This is the reason why all figures are not universally applicable.

At the end of this bachelor thesis, a table will be showing an overview of the different fasteners and joining techniques while compares them depending on important parameters.

2 Modular Timber Construction

2.1 Definition of Modular Construction

The term modular construction describes a process in which parts of buildings are prefabricated in factories. Volumetric construction consisting of various panels are produced, which are called modules. These modules have the same standard as conventionally build constructions and are made out of the same materials. When being transported to a construction site, several modules can form a final building design. Elements are formed to different components, which are then put together into panels. If several panelised constructions are assembled, modular structures are created (Ferrer, n.d.; Modular Building Institute, n.d.).



(Ferrer, n.d.)

Figure 1: Meaning of modular construction

2.2 Areas of application

Modular construction can be used for different types of buildings, both permanent and temporary. Possible building types for modular timber constructions are (Jakob, 2019):

- Educational buildings
- Residential properties
- Administration buildings
- Hospitals

Modular construction cannot only be used in combination with other modules, but they can also be used to connect timber modules to existing buildings, regardless of the building type. For example, a traditional brick building can be extended with a modular timber construction. The light weight of timber structures makes it possible to expand an existing building with a new floor made of a modular timber construction on top of the building. This way, the lifetime of a building can be increased by adding new floors to a building instead of tearing it down and building a new structure. Consequently more people are able to live in a certain building which increases the population density (Auclair, 2022; Horx-Strathern et al., n.d.).

2.3 Strengths and Challenges of Modular Timber Construction

The possibility of prefabrication leads to several positive aspects for modular timber construction. For modules, a degree of prefabrication of up to 95% is possible. After all modules of a certain building are prefabricated off-site, they are transported to the construction site. There all modules can be assembled to form a new building design. Because of prefabrication, the speed of completing a building is 30-50% higher than the time it takes to complete a building when not using prefabricated modules. During the prefabrication of the modules, the foundation work can be done in parallel on the construction site which saves time.

Prefabrication in a factory improves the working conditions for the people and provides better work equipment such as better tools like saws, CNC-machines and ceiling cranes. Working in a factory building means that the workers and the building materials are not exposed to the weather. The availability of better tools can also increase the quality of the construction and accelerate the production. By using computer-controlled production processes for CLT for instance, the openings for windows and doors can be omitted during production to save material. This process can save up to 50% of waste through the use of advanced technologies (wsp, 2018).

During the lifetime of a building, it is possible to expand a building with new modules or to downsize it. The modules, which are removed can either be sold or used for a different building. In some cases, a possible damage can easily be repaired by replacing modules. This type of variability increases the lifespan of a building, as it can be adapted to current needs effortlessly.

If the demands on the building change, the building is no longer needed or is too old, the modules can be deconstructed. Up to 70% of the value can be retained and reused. This has a positive effect on the circular economy by saving building materials and positive effects on the environment by saving CO_2, which is needed to produce several building materials. Furthermore, it is cheaper to reuse a module or parts of it, than buying a new one, this is why money can be saved (SH-Modul Bau GmbH, n.d.).

Besides the positive aspects of prefabrication, there are also some positive aspects due to the characteristics of wood. Wood has good thermal insulation and is a light material compared to concrete, bricks and steel. This saves thermal insulation materials and CO_2 which is produced when heating up the building. Due to the low weight of wood, the transport is more economical and consumes less CO_2 because more wood than, for instance, concrete can be transported depending on the specific weight. In addition, wood is one of the most sustainable building materials, which is an important aspect for the competitiveness of timber construction and the whole building industry.

However, prefabrication does not only have positive aspects. One disadvantage of the prefabrication is the transportation of the prefabricated modules. When transporting the modules, there are regulations which are prescribed by the government that must be followed. The transport dimension limits and payload limits of Germany are shown in Table 1 and Figure 2 below. Consequently, the size of a module has to be taken into consideration before designing a module to not overgo transportation guidelines (Moro and Schlaich, 2022).

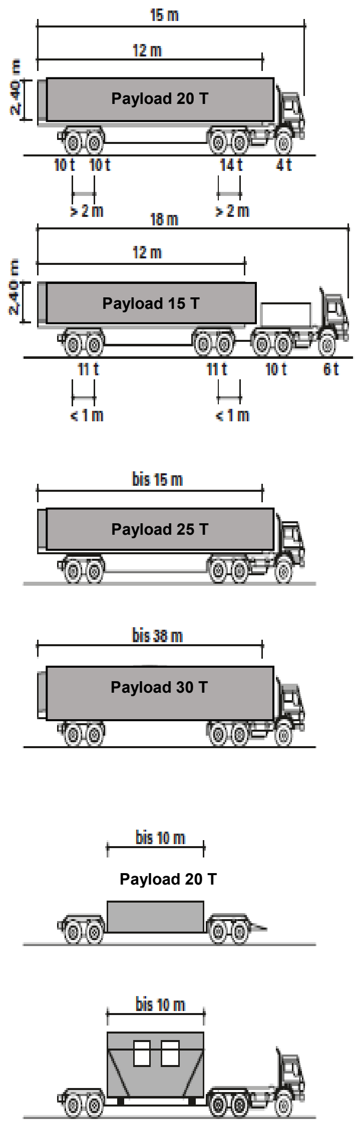
Table 1: Transportation dimension limits in Germany

Special permission	Width [m]	Heigh [m]	Length [m]
No	<2,5	<4,0	<18,0
Yes, without any police escort on German country roads	<3,5	-	<24,0
Yes, without police escort on German highways	<4,5	-	<28,0

(Moro and Schlaich, 2022)

Mass production can be advantageous for buildings in modular timber construction. In order to achieve mass production, the modules must be standardized. Furthermore, a high number of identical modules is required for a mass product, which limits the architectonic factor. By using a high number of identical modules, only some parts such as the ground layout or the facade can be changed architecturally. To reconcile all the factors with the interests of the client is a challenge of mass production. Concerning mass production, it is very important to take under consideration that a certain design for a module needs to be found, so that it is suitable for the majority of clients. This a real challenge when it comes to mass production.

If a client changes his mind about what the modules should look like during the manufacturing process, it can have a big impact on the structural design. The lower floor modules, the connection between the modules and on an arrangement that has been established since the design phase, need to be changed. Consequently, the building must almost be completely thought through in the early design phase and modification is usually not possible. This results in a high degree of planning, which joins together all the interests of the client and construction aspects, which becomes a challenge for the planning of modular construction.



(Moro and Schlaich, 2022)

Figure 2: Loading dimensions and payloads for the transport of prefabricated elements

Another challenge of modular timber construction is that only a few companies offer modular timber construction as a service. Those companies do not share their knowledge with the public. Therefore, it is difficult obtain information, pictures and drawings (Goetz, 2023; SH Holz & Modulbau GmbH, 2023). This lack of information needs to be closed by collection experience in modular timber construction. As modular conception is a promising construction sector, more information needs to be gathered to further develop concepts for modular timber construction.

For those reasons, most of this bachelor thesis is based on concepts without any practical experience. A further challenge of modular timber construction is to use positive-lockings. Since interlocking connections require high precision, this can lead to difficulties. For example, CLT is already delivered with dimensional deviations and more deviations are also to be expected when assembling the modules, which makes precise work difficult (SAINT GOBAIN Brüggemann Holzbau GmbH, 2023). The following Table 1 defines the allowed tolerances of inaccuracy in CLT products (Ingenieur Holzbau.de, 2021; SAINT GOBAIN Brüggemann Holzbau GmbH, 2023).

Table 2: Tolerances at a measurement reference humidity of 12 %

Panel thicknesses	for t ≤ 300 mm for t > 300 mm	± 2 mm ± 3 mm
Panel widths and openings	for b ≤ 3,000 mm for b > 3,000 mm	± 2 mm ± 3 mm
Panel lengths	for ℓ ≤ 3,000 mm for 3,000 < ℓ ≤ 10,000 mm for ℓ > 10,000 mm	± 3 mm ± 4 mm ± 5 mm

Furthermore, practical experience has shown us that elements and components may not always be perfectly straight and surfaces of materials may be uneven. All points together lead to difficulties in working precisely. To adjust the deviations of the modular timber construction and the foundation the connections should be able to level (SAINT GOBAIN Brüggemann Holzbau GmbH, 2023).

Another issue is the size and mass of the modules. Due to the size of the modules, manoeuvring them by crane might be difficult because the view is limited. In addition, the large dimension of the modules leads to the danger that the module rotates due to wind forces. Because of the mass, manoeuvring is also difficult because more force is needed to position the module. These two facts make it difficult to guide them into precisely fitting connections.

However, the properties of wood also have negative aspects. Wood is a poor sound insulator and a combustible material. Because of these two points, it is more complicated to design the walls, floors and ceilings to ensure a good sound insulation.

In Table 3 below all positive aspects and challenges of modular timber construction are summarized.

Table 3: Positive aspects and challenges in modular timber construction

positive aspects:	challenges:
sustainability	sound insulation
circular economy	fire resistance
material saving	transport regulations
thermal insulation	mass production
light weight	planning
prefabrication	lack of information and experience
pace of construction	
no weather exposure	
working conditions for humans	
quality due to prefabrication	

2.4 Types of Modular Timber Construction

Modular timber construction can be produced in different ways. They vary in the way the walls, ceilings, floors or the load-bearing structure is made.

Skeleton Construction:

Construction:

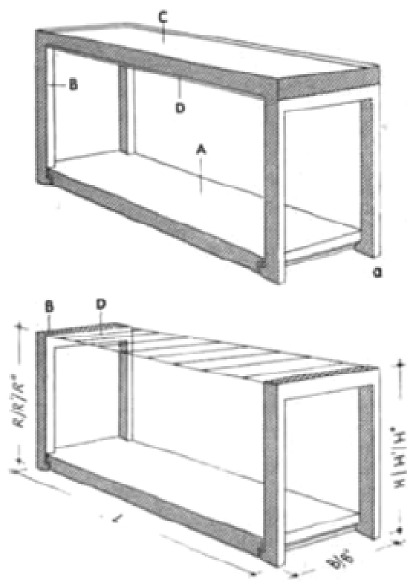
In skeleton construction, the loads are transferred through a supporting framework based on the truss principle. Modular timber construction which is made in this way consists of vertical columns and horizontal beams that are connected to each other in the corners. The load bearing elements of a skeleton construction are presented in Figure 3 below. In this way, distances of up to 5m can be achieved between the supports. The areas between the supporting elements are filled with thermal insulation material and then planked with wood-based panels and gypsum board.

Building Physics Properties:

Fire protection and sound insulation are fulfilled by technical installations. The quality of the thermal insulation products covers the requirements of the thermal insulation (Jakob, 2019).

Intended use:

- additions and building extensions
- well suited for adding storeys to existing buildings due to the lower weight apartment buildings, functional and commercial buildings
- private residential construction



(Huß, Kaufmann and Merz, 2018)

Figure 3: Skeleton construction module

Timber frame construction:

Construction:

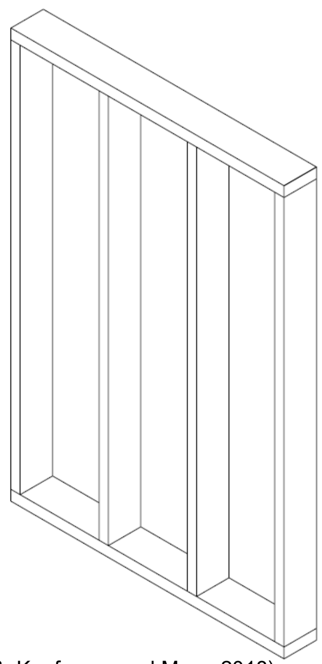
In timber frame construction, as the name implies, the walls consist of a timber frame. In this process, vertical uprights are in a particular distance and connected via beams. As it can be seen in Figure 4, a timer frame construction is used without any planking. This part of the penalized component creates the load bearing structure. The stiffening is formed via the planking on both sides with wood-based panels and gypsum board. In this construction, unlike skeleton construction, the loads are transferred through the walls.

Building Physics Properties:

The compartments of the timber frame construction are fulfilled with thermal insulation material. The fire resistance and the sound insulation are improved by technical installations (Jakob, 2019).

Intended use:

- additions and extensions to buildings
- due to the lower weight, well suited for the addition of floors to existing buildings
- multi-family houses, functional and commercial buildings
- private residential construction



(Huß, Kaufmann and Merz, 2018)

Figure 4: Timber frame penalized construction

Solid wood construction:

Construction:

CLT is a flat wood product and is used as a load-bearing element for walls, floors and ceilings. The CLT consists of at least three layers of softwood, which are joined together at right angles. These can be manufactured in large dimensions. A picture of the assembling of a modular timber construction with CLT is shown in Figure 5. Due to the arrangement of the wood layers, the product is able to carry loads in all directions and also provide stiffening, as it is a stiffened slice itself.

Building Physics Properties:

Fire protection and sound insulation requirements can be met by a multilayer wall and ceiling/floor construction. The surface material and cross-connected layers in CLT prevent swelling and shrinkage. Nevertheless, low component heights and low component weights allow load transfer over large areas. The characteristics of CLT also have a positive effect on moisture and heat storage capacity (Jakob, 2019).

Intended use:

- multi-residential construction, private residential construction, functional and commercial buildings
- extensions and building enlargements
- well suited for extensions due to the low weight
- events and other short-term uses

(Huß, Kaufmann and Merz, 2018)

Figure 5: Solid wood module

2.5 Airtightness

In modular timber construction, the air-tight level is created from the inside of the exterior wall by using a foil. In order to connect the airtight layer between the modules, the foils in the ceiling/floor panes must be connected to each other. The foil between the wall and the ceiling/floor is led to the outside where it is connected. The process of inserting the foil in between the contact gaps can be complicated if fastener or connection techniques are placed in the same contact gap. In order to prevent the foil from being punctured, the stiffening slices of the building should, if possible, not be located in the outer wall. If this should nevertheless be the case, joints such as the plain scarf joint or mortise and tenon joints have a disadvantage compared to e.g., nail plates. The reason for this is that the foil guide is disturbed by notches and protruding components.

The following Figure 6 shows an example how the airtight layer could be produced with the outer wall of a modular wooden construction and the laying path of the airtight layer. As the figure demonstrates the foil is going into the contact gap of the stacked module to the outside of the exterior wall.

To line up the modular timber construction, the airtight layer is constructed by using the same technique. The foil is going in the corner of the inner and outer wall to the outside of the exterior wall, where it is connected with the foil of the next modular timber construction (SAINT GOBAIN Brüggemann Holzbau GmbH, 2023).

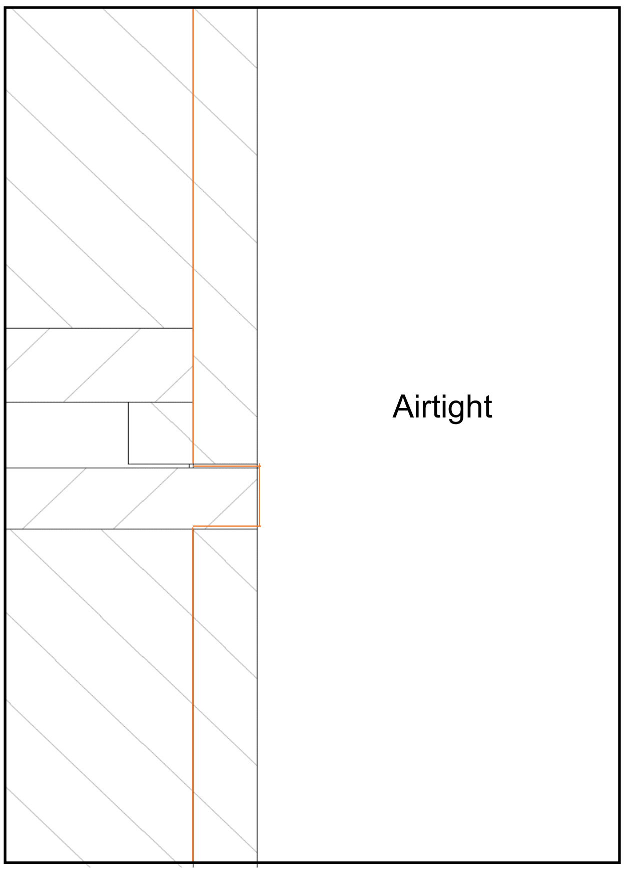


Figure 6: Airtight layer between two stacked modules

3 Loads on the fasteners

Since the main topic of this paper is the inter-module connection of several modules of a building, this section examines the possible loads at the intersections and junctions between modules. The fasteners must support vertical loads from own weight, payloads and variable loads.

In addition, all loads, that result from wind, must be absorbed and transferred by the fasteners and connection techniques to redirect the forces downwards. Wind can cause horizontal forces and also vertical uplifting forces. Lifting forces can also occur, for example, during earthquakes. However, earthquakes do not occur in all regions of the earth. Therefore, this effect can be treated separately if the construction site is located in an earthquake zone. Therefore, this effect can be individually taken into account if the construction site is located in an earthquake zone.

Another cause of uplifting forces is the number of stiffening wall slices in a building direction, regardless of whether uplifting forces occur or not. A low number of vertical stiffening slices, for example, leads to a high load concentration and thus to larger forces or uplifting forces (SAINT GOBAIN Brüggemann Holzbau GmbH, 2023).

In the figures below possible load cases are clarified. To explain the forces that can occur, these arrows and colours were used:

- acting force:
- tension:
- pressure:
- shear forces:
- modular timber construction:
- displacement, torsion of the modular timber construction due to the acting force:

Figure 7 and Figure 8 below demonstrate how the acting force has an impact on the stacked modules. The upper module in Figure 7 is tilted due to the acting force. This leads to tension forces in the left contact gap. In Figure 8, the upper module is sliding and guides to horizontal shear forces in the horizontal contact gap of the stacked modules.

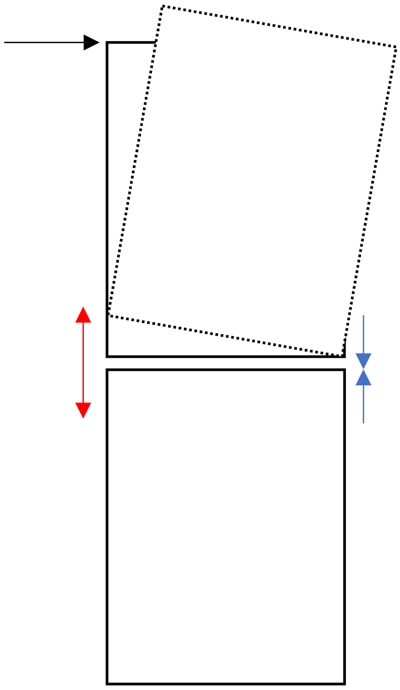


Figure 7: Front view: Tension through uplift

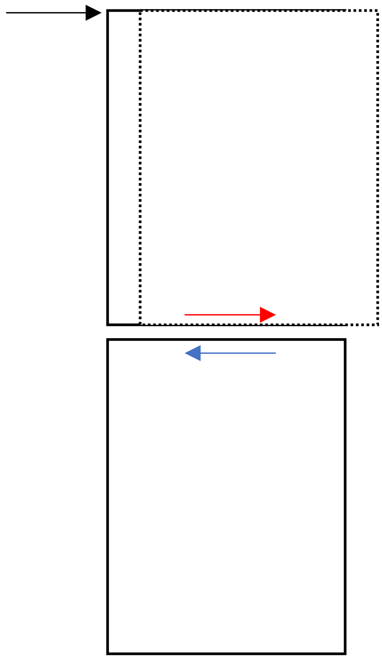


Figure 8: Front view: Horizontal shear forces

The tilt of a module also has an impact on rowed modules. In the connection point on top of the module, it leads to pressure forces, which are illustrate in Figure 9, or to tension force which are demonstrate in Figure 10

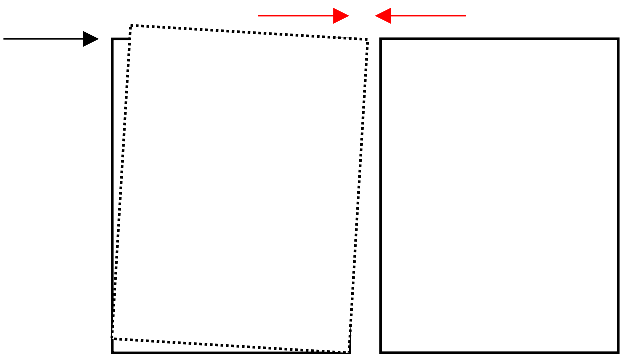


Figure 9: Front view: Horizontal pressure forces

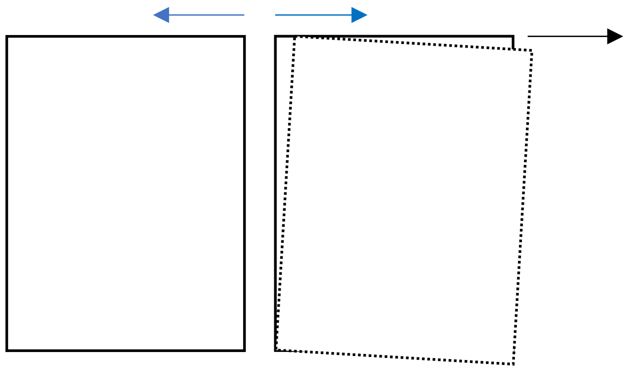


Figure 10: Front view: Horizontal tension forces

Shear forces also can appear in the vertical contact gap between rowed modules. To clarify this occurrence, Figure 11 shows the top view of two modules next to each other.

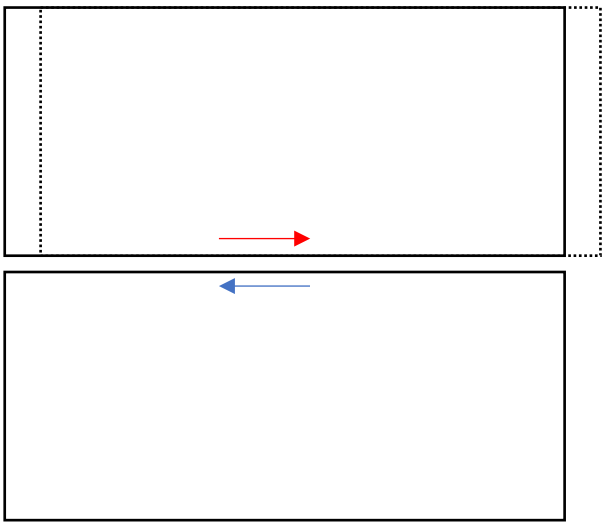


Figure 11: Top view: Vertical shear forces

As a result of wind, a twisting of the structure may occur. To prevent this, horizontal slices and vertical slices must be constructed by connecting the modules with fasteners/connection techniques. The reason that vertical and horizontal panels have to be added is that not all modules have enough stiffening walls. Thus, the forces that lead to torsion of the modules through the formed slice are diverted and stiffened.

The torsion is illustrated in Figure 12 below. On the left hand side a module is shown from the front perspective and on the right hand side a module, which is twisted due to the acting force, is presented from the side view.

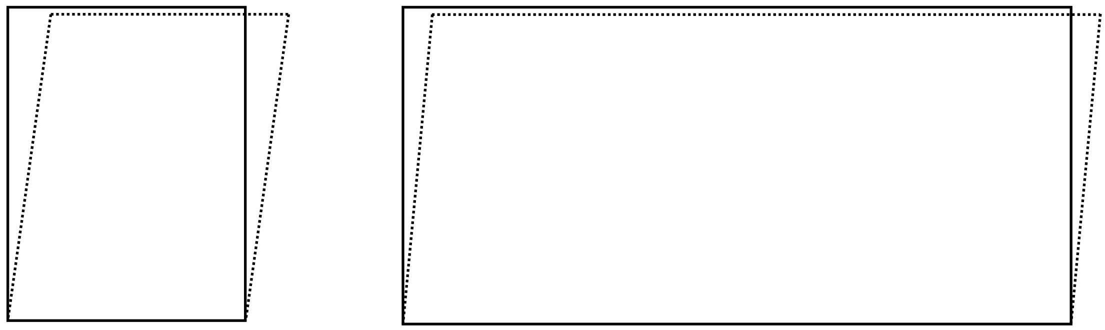


Figure 12: Torsion within a module

4 General Properties of Connections

4.1 Different Types of Connections

Form-fit connection:

Form-fit connections are used when the components that need to be joined are adjusted in a certain way, so that they interlock and are secured in position. When using form-fit connection, precise work is needed from the preparation to the assembly, in order to ensure that the interlock and the two connecting parts are accurately joined (Marquardt, n.d.).

Examples:

- dovetail joint
- mortise and tenon

Force-locking:

Force-locking occurs when two materials are joined together by forces such as pressure or friction (Marquardt, n.d.).

Examples:

- nail
- screw
- hook connector

Substance-locking:

Materially bonded joints are any joints in which the components are held together by atomic or molecular forces (Marquardt, n.d.).

Example:

1. gluing

4.2 Standard Connection between Timber Modules

Within a building, the loads that need to be applied at the connection points, differ. Therefore, this bachelor thesis distinguishes between standard connections and special connections.

Standard connections are the connections that secure the position in the horizontal slice. In this case, shear forces must be absorbed and, in addition, pressure and tension forces have to be absorbed in the ceiling slap (SAINT GOBAIN Brüggemann Holzbau GmbH, 2023).

4.3 Special Connections in Modular Timber Construction

Special connections are used to absorb loads that do not necessarily occur. Thus, the absorption of lifting forces is a special connection. In some buildings, there are no lifting forces and that is why in this case, fasteners or connection techniques can be omitted (SAINT GOBAIN Brüggemann Holzbau GmbH, 2023).

The height of a building has an influence on the development of lifting forces. The taller the building, the more likely it is that lifting forces will occur. Consequently, low building heights may mean that lifting forces do not occur and for this reason, no special fasteners need to be installed for these loads (SAINT GOBAIN Brüggemann Holzbau GmbH, 2023).

5 Friction

Friction is a physical force that works against an object as its slides along the surface of another object and occurs in any contact area. It also occurs between two stacked modules. The use of friction in a static calculation is not standardized because it is not covered by EC5 (DIN EN 1995) and is therefore not taken into account. In DIN EN 1995-1-1/NA, the allowable approach of friction was only considered between woods with resiliently bonded layers.

This topic explains what friction is and gives a brief insight into friction coefficients, but friction itself is not taken into account at the end of this thesis.

Static friction is when the friction force F_R is bigger than the acting force F and prevents an object from moving. The principle of friction and how the forces are acting is illustrated in Figure 13. The formular of static friction shows, that a higher coefficient of friction is better to carry horizontal shear forces.

The formular for static friction is:

$$F_R = \mu_S \cdot F_N$$

$$F_N = normal\ force$$

$$\mu_s = friction\ coefficient$$

$$F_R = Friction\ Force$$

$$F = Acting\ Force$$

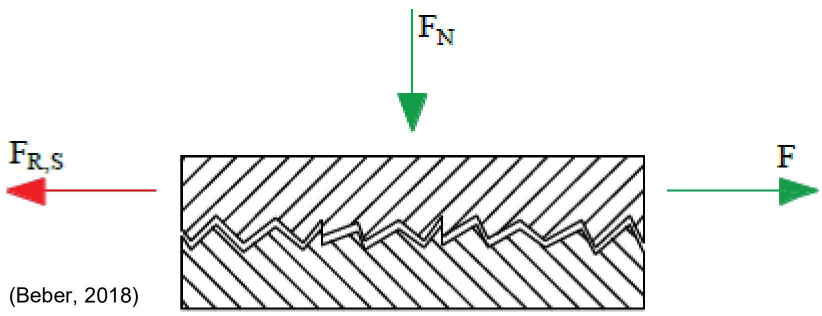


Figure 13: Static friction

Each material has different characteristics in friction and there are many different influences on the coefficient of friction. For example, the type of wood, the moisture content and the alignment of the wood all affect the coefficient of friction (Beber, 2018).

Planed spruce for example has an average coefficient of 0.5 at 10-17% moisture content (Möhler and Maier, 1969).

The coefficient of friction between the elastomeric bearing Xylophone and planed spruce wood is approximately 0.5 (Rothoblaas, 2023).

6 Fasteners and Connection Techniques

6.1 Elastomeric Bearing

Static Properties:

There are large differences in applicable pressure loads. The reason for these differences is the material itself and the final versions of the product. The version of the elastomeric bearing is different in shore hardness (Rothoblaas, n.d.e). Shore hardness is the resistance of a rubber sample to the penetration of a cone-shaped body of a given dimension under a defined compressive force (Die Shore-Härte, n.d.).

Structural Properties:

Elastomeric bearings are sound-absorbing building materials that are used in between two surfaces and require no preparation. They are either placed between structural elements during installation or are attached previously to structural elements. Depending on the requirements, elastomeric bearings can be used in linear or point applications (Eurotec, 2021; Rothoblaas, n.d.e).

Building Physical Properties:

The main purpose of elastomeric bearings is to reduce structural noises. This is an important detail which can be challenging in wood construction. By using elastomeric bearings in contact joints of structural members, to connect two modules, it is possible to reduce up to 15 db. of volume (Eurotec, 2021; Rothoblaas, n.d.e).

Examples of Elastomeric Bearing:

Figure 14 displays an elastomeric bearing for which environmentally friendly materials were used. The core of the bearing consists of sand and the surface is made of paper. Due to the sand, a high fire resistance is achieved. However, it must always be protected from water because otherwise the paper surface could be damaged (Wolf Bavaria, n.d.).

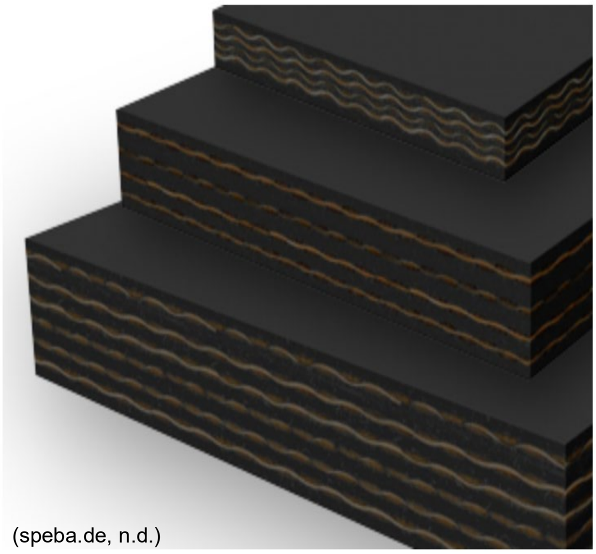
Figure 15 shows an example of the manufacturer Speba. Different elastomeric bearings with different strengths and building physical properties like fire resistance and thermal insulation are used, depending on the required function of the element. Elastomeric bearings are made of synthetic rubber or rubber-like synthetic material (Speba Innovative Bautechnik, n.d.).

The fourth example of elastomeric bearings in Figure 16 shows the product Xylophone. This product is made ofp polyurethane and is available in different versions depending on how much load it has to carry. Xylophone is a fire-resistant material and is classified in fire resistance rating EI60 (Rothoblaas, n.d.e).

As you can see in Figure 17 an elastomeric bearing made of cork is utilized. Cork is a renewable raw material and achieves a higher sustainability compared to elastomeric bearing out of polyurethan or other synthetic materials (Eurotec, 2021).

(wolf-bavaria.com, n.d.)

Figure 14: Elastomeric bearing “Phonestar Schalli”



(speba.de, n.d.)

Figure 15: Elastomeric bearing of manufacturer Speba

Figure 16: Elastomeric bearing “Xylophone”

Figure 17: Elastomeric bearing cork

6.2 Carpentry Joints

6.2.1 General Properties of Carpentry Joints

Carpentry joints are making use of the specific characteristics of wood to connect building components. In the past, those connections were made with hand tools and have a long tradition. Nowadays, carpentry joints are made by machines, but the traditional craft joints have proved themself and are still used today (Baunetz Wissen, n.d.; Bundesbildungszentrum des Zimmerer- und Ausbaugewerbes, n.d.). All carpentry joints which are presented are form-fit connection to absorb the acting forces. Therefore, a higher precision is necessary compared to connection via force-lockings like perforated plates. In terms of sustainability, carpentry connections are classified as a sustainable connection technology in the final table. This is due to the use of the renewable raw material wood compared to steel and aluminium.

The specific characteristics of wood are considerable by comparing the strengths values in Table 4. When it comes to timber construction, wood class C24 is commonly used. The strength in longitudinal fibre direction is significantly higher than the strengths across the fibre direction regardless of tension or pressure forces that occur. Because of those reasons carpentry joints are designed to use the strong directions of wood (Albert et al., 2018; Baunetz Wissen, n.d.; DIN Deutsches Institut für Normungen e.V., 2016).

Table 4: Strength classes for softwood based on edgewise bending tests-values for strength, stiffness and gross density

	Class	C14	C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50
Strength properties, in N/mm2													
Bend	$f_{m,k}$	14	**16**	**18**	20	22	**24**	27	**30**	35	40	45	50
Tension in fibre direction	$f_{t,0,k}$	7,2	**8,5**	**10**	11,5	13	**14,5**	16,5	**19**	22,5	26	30	33,5
Tension perpendicular to the grain direction	$f_{t,90,k}$	0,4	**0,4**	**0,4**	0,4	0,4	**0,4**	0,4	**0,4**	0,4	0,4	0,4	0,4
Pressure in fibre direction	$f_{c,0,k}$	16	**17**	**18**	19	20	**21**	22	**24**	25	27	29	30
Pressure perpendicular to the grain direction	$f_{c,90,k}$	2,0	**2,2**	**2,2**	2,3	2,4	**2,5**	2,5	**2,7**	2,7	2,8	2,9	3,0
Thrust	$f_{v,k}$	3,0	**3,2**	**3,4**	3,6	3,8	**4,0**	4,0	**4,0**	4,0	4,0	4,0	4,0
Stiffness properties, in kN/mm2													
Mean value of the modulus of elasticity for bending in the fibre direction	$E_{m,0,mean}$	7,0	**8,0**	**9,0**	9,5	10,0	**11,0**	11,5	**12,0**	13,0	14,0	15,0	16,0
5% quantile of the modulus of elasticity for bending in the fibre direction	$E_{m,0,k}$	4,7	**5,4**	**6,0**	6,4	6,7	**7,4**	7,7	**8,0**	8,7	9,4	10,1	10,7
Mean value of the modulus of elasticity in bending at right angles to the fibre direction	$E_{m,90,mean}$	0,23	**0,27**	**0,30**	0,32	0,33	**0,37**	0,38	**0,40**	0,43	0,47	0,50	0,53
Mean value of the shear modulus	G_{mean}	0,44	**0,50**	**0,56**	0,59	0,63	**0,69**	0,72	**0,75**	0,81	0,88	0,94	1,00
Bulk density, in kg/m3													
5% quantile of the bulk density	ρ_k	290	**310**	**320**	330	340	**350**	360	**380**	390	400	410	430
Mean value of the bulk density	ρ_{mean}	350	**370**	**380**	400	410	**420**	430	**460**	470	480	490	520

NOTE1 Theabove values for tensile, compressive and shear strength, characteristic modulus of elasticity in bending, mean value of modulus of elasticity perpendicular to the grain direction and mean value of shear modulus have been calculated using the equations given in EN 384.

NOTE 2The tensile strength values have been estimated on the safe side as grading is done for flexural strength.

NOTE3 Thetabulated properties apply to wood with a normal wood moisture content at 20 °C and 65 % relative humidity, which corresponds to a wood moisture content of 12 % for most wood species.

NOTE 4 The characteristic values for shear strength are given according to EN 408 for timber without cracks.

NOTE5 Theseclasses may also be used for hardwood with similar strength and density profiles, such as poplar or chestnut. NOTE6 The high bending strength may also be used in the case of flat bending.

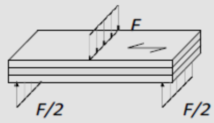
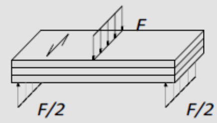
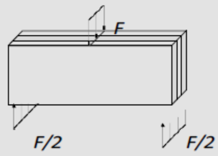
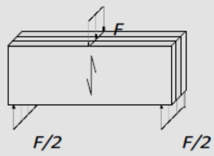
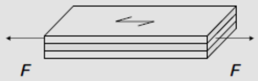
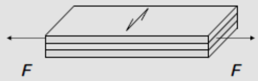
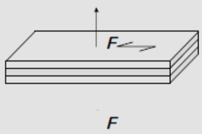
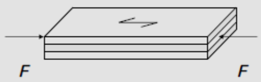
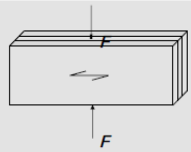
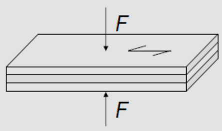
The construction industry is constantly developing new and better materials and has created the material CLT in the past. As already mentioned in section 2.4 in the solid wood construction part, CLT consists of at least three layers which are glued orthogonally. By gluing the layers in a 90-degree angle, a significantly higher strength in both directions is achieved. The possibility of using CLT, instead of the softwood C24 can improve the strength of carpentry joints such as the dovetail or wooden lugs. On the one hand due to the strength in both orthogonal directions, the dovetail or wooden lug can absorb shear forces and the other direction tension or compressive forces. But on the other hand, due to the change of the direction of the fibres, it could lead to the occurrence of shear forces in the glued contact gap in between the layers which could lead to the weakening of the material. By choosing a larger dimension of the wood, shear forces in the glued layer can be absorbed. The values of the strength are displayed in Table 5 in connection with Table 6. To explain the strength of tension, compressive and shear forces in CLT it is important to bear in mind, that they are not arranged in the direction of the fibres, but in the panel layer, and thus in both orthogonal directions. Consequently they have the same values, because the forces are the same in every direction (informationsdienst-holz.de, 2021).

Table 5: Minimum values of the strength and stiffness characteristics of the solid wood layers [1)]

Feature [2)]		Symbol	Value
Flexural strength [3)]	For bending moments perpendicular to the panel plane	$f_{m,k}$	24
Tensile strength	At panel level	$f_{t,0,k}$	14
	Perpendicular to the panel plane	$f_{t,90,k}$	0,12
Compressive strength	At panel level	$f_{c,0,k}$	21
	Perpendicular to the panel plane	$f_{c,90,k}$	2,50
Shear strength [4)]	Longitudinal	$f_{v,k}$	3,50
	Roller drawer	$f_{r,k}$	0,70
Modulus of elasticity [5)]	At panel level	$E_{0,mean}$	11.000
	Perpendicular to the panel plane	$E_{90,mean}$	370
Shear modulus [5) 6)]	Perpendicular to the panel plane	G_{mean}	650
	Roller drawer	$G_{r,mean}$	50
Bulk density		ρ_k	385

1) For verifications on the net cross-section.
2) See also Table 6.
3) For bending moments in the slab plane, e.g. for the design of columns and cantilevered panels, the characteristic value of the vertical bending strength in the slab plane $f_{m,edge,k}$ is required. This cannot usually be taken from the abZ or ETA.
According to FprEN 16351:2020, a value of $f_{m,edge,k}$ = 20.5 N/mm2 can be applied. Manufacturer's specifications must be observed.
4) For verifications of the shear strength on the total cross-section or the torsional shear strength of the bonded intersection surfaces of the lamellae of adjacent solid wood layers, further characteristic values are required that usually cannot be declared on the basis of the abZ or ETA. According to FprEN 16351:2020, $f_{v,xy,k}$ or $f_{v,yx,k}$ = 5.50 N/mm2 can be used as the shear strength of the total cross-section.
For the torsional shear strength of the crossing surfaces, $f_{tor,node,k}$ = 2.5 N/mm2 is specified. Manufacturer's specifications must be observed.
5) The 5% quantiles of the elastic and shear moduli may be assumed to be 5/6 of the mean values: E05 = Emean - 5/6 and G05 = Gmean - 5/6
6) A value of Gxy = 250 N/mm2, which is usually not declared on the basis of the abZ or ETA, can be assumed as the shear modulus in the panel plane. Manufacturer's specifications must be observed.

Table 6: Explanation of the strength and stiffness values given in Table 5

Stress		Characteristic values for the verification of layers in fibre
		f_m f_v and f_r E_0 G and G_r
		$f_{m,edge}$ $f_{v,xy}$ and $f_{tor,node}$ E_0 G_{xy}
		$f_{t,0}$ $E_{t,0}$
		$f_{t,90}$ E_{90}
		$f_{c,0}$ $E_{c,0}$
		$f_{c,90}$ $E_{c,90}$

6.2.2 Cleat

Static Properties:

In timber construction, the cleat is a connection technique that transfers the horizontal shear forces of a beam to a parallel offset structural element. In rafter roofs, for example, the load is transferred from the rafters to the support with cleats. In modular timber constructions, cleats in combination with cut-outs are used to absorb the horizontal shear forces and redirect them downwards into the lower module.

Structural Properties:

The cuts-outs, which are needed to secure the cleat and to transfer the shear forces, are made by CNC-machines. The cleat itself can be produced by hand tools or can also be made by CNC-machines. During assembly, the cleat can be prepared and screwed onto the modules. This preparation can be done simultaneously with the assembly of the modules. If two modules are stacked, the module on the top is placed in the cut-out. Therefore, the position is secured and no additional fasteners are required. If uplift forces occurring in modular timber construction additional fasteners or connection techniques are needed. The creation of the horizontal slice can be done simultaneously with the construction or after each floor. For creating the horizontal slice, additional fasteners or connection techniques are essential. To clarify this concept, Figure 18, shows the prepared cleat on top of the modules. In the middle of the figure the finished connection with cleats inside the wall is presented and at the bottom of the figure the cut-outs for the joining wood are shown. When using a stacking system, a higher degree of prefabrication can be achieved than when using connectors such as nail plates or similar. Form-fit connection does not require screws and the facade can be finished before stacking the modules. This can only be the case, if the airtight layer is not taken into consideration. For systems that need screws, the facade cannot be finished beforehand because the fasteners need to be installed after the erection. Even the disassembly is easier when using these form-fit connections because there are no screws inside the connection.

Building Physical Properties:

Elastomeric bearing can be inserted within the cut-outs in order to be able to guarantee the required sound insulation. If cleats are necessary inside the exterior wall and the airtight layer, this can cause airtightness problems by making it difficult or impossible to insert the foil. The reason for the problems is that the straight path through the contact gap is blocked by the cleats. Concerning fire resistance properties, the cleat has no influence. The reason for this is that the cleat is placed inside the wall and is protected by CLT. The only part which can come in contact with fire is in between the modules next to each other and in between stacked modules. The places that are most likely to catch fire are the corners. Since the cleats are inside the wall, almost no corners exist and the whole wall can be described as one surface. This is why the danger of catching fire is minimized.

Other Characteristics:

Due to the size of wooden modules, the connecting timber can be made from scraps and is also a more sustainable raw material than metal connectors. Another sustainable factor of the stacking system, is that it increases the circular economy of building materials because it causes less damage during deconstruction. In addition, this connection does not require fasteners and this system has a high installation speed, compared to perforated plates or similar fasteners, which has a positive impact on cost-efficiency. Form-fit connections have also a negative aspect. If it is necessary to adjust the level of a modular timber construction because the lower module is not perfectly in level, it could lead to problems. By balancing out the modules with a cleat connection, it could cause difficulties in the load transmission as the contact gap is extended and the form-fit connection does not fit anymore.

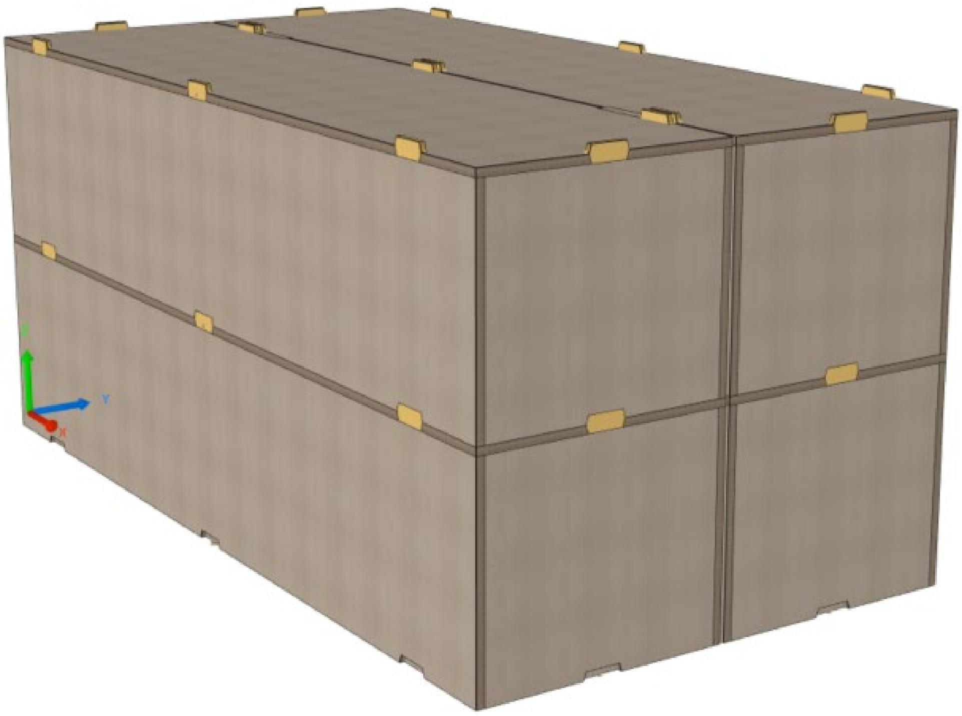


Figure 18: Modular timber construction with cleats

6.2.3 Wooden Lug

Static Properties:

The wooden lugs which are shown in Figure 19, are used to form the ceiling slice. By creating the slice, the wooden lugs are carrying the horizontal pressure, horizontal tension forces and vertical shear forces (SAINT GOBAIN Brüggemann Holzbau GmbH, 2023).

Structural Properties:

While the wooden lug is cut out with CNC-machines off-site, the lug itself is inserted into the recess on site. The modules are connected by using screws to guarantee their proper position and for absorbing the tension forces in the horizontal slice. The screws are stressed by shearing. Otherwise, the pressure forces are carried by the form-fit connection. Because of the form-fit connection, it can be difficult to work precisely during the erection of the modules. The degree of prefabrication and the accessibility during assembly has no influence on the use of timber lugs as a connection technique for modular timber construction, since the lugs are inserted into the ceiling from above, after each floor is built.

Building Physical Properties:

The fire resistance can be regulated by choosing a bigger dimension of the lug. The bigger the lug, the higher the fire resistance. The wooden lugs itself has no impact on the airtight layer, because they cannot be used at the exterior wall. Concerning the sound insulation aspects, it can be said, that the lugs do not have any influence on it since elastomeric bearing can easily be put in between the wooden lugs and the module.

Other Characteristics:

The wooden lugs are assembled on top of the modules, which leads to the possibility of screwing the lugs into the cut-out during the erection or after each floor is built. Therefore, it is possible to place all modules of one floor in the right position at first and then start to connect the modules afterwards. If a floor consists of several modules, it is more efficient to set up all modules at first, so that the crane does not have to wait for a long time. In the next step, all modules can be connected by applying wood lugs from top of the module. In the same step, if necessary, the next floor can be adjusted in level by using steel compensation plates, for example. The wooden lugs have no influence on the adjustment because it is created in the contact gap between the stacked modules and the wooden lugs are located inside the ceiling. Thus, the productivity can be improved, as waiting times are minimalized. Additionally, through the use of screwed connections, this system is deconstructable. Not only because of the deconstructability, but because of the material wood itself, this connection technique can be classified as sustainable.

The following Figure 19 shows the top view of modular timber construction connected with wooden lugs.

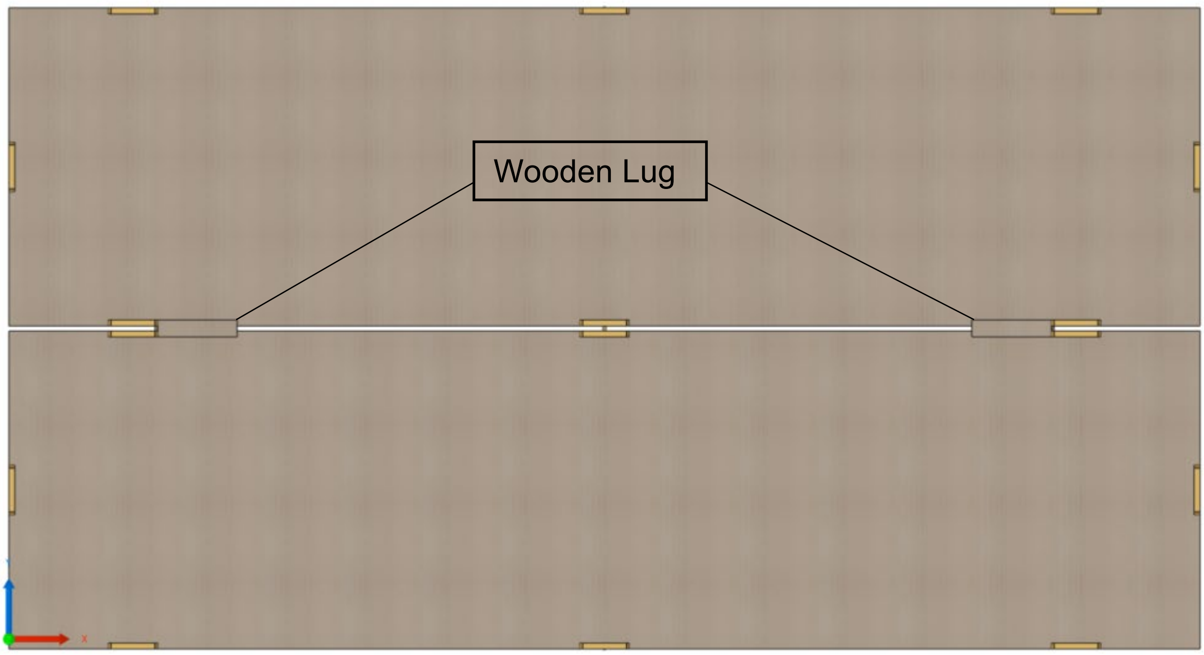


Figure 19: Top view: Modular timber construction with cleats and wooden lugs

6.2.4 Dovetail Joint

Static Properties:

The dovetail joint can absorb uplift forces, shear forces, pressure forces and tension forces. If uplift forces are carried by dovetails, they can be classified as special connections. Inside the walls, the dovetails absorb the vertical shear forces and the vertical uplift forces. In the ceiling, dovetails are provided to take in the horizontal compressive, horizontal tension forces and horizontal shear forces. In addition, they form a horizontal slice against torsion caused by wind (Baunetz Wissen, n.d.; Bundesbildungszentrum des Zimmerer- und Ausbaugewerbes, n.d.).

Structural Properties:

The carves, where the dovetail is placed into, can be made by CNC-machines just as the dovetail. The erection of modules with dovetails is more difficult than a stacking system such as cleats. The modules need to be placed precisely on top of the lower module and the dovetail need to be small enough to get in between two rowed modules, when the dovetail is put into the cut-out. When using dovetails to connect two modules at the facade, the degree of prefabrication is important. In the spots where the modules are connected, the facade must be finished afterwards.

Building Physical Properties:

In order to provide sound insulation with this construction, an elastomeric bearing can be used in between the carves and the dovetail. Concerning fire resistance, the area between the rowed modules is more vulnerable, because the cross-section is smaller and the edges are more likely to catch fire. The rest of the dovetail has no influence on the fire resistance due to the fact that it is located inside the CLT wall or ceiling. Dovetails should not be placed in the exterior wall, as it could lead to problems with the foil of the airtight layer, because they are located in the place where the foil is connected to the foil of the module on top or the module below.

Other Characteristics:

The preparation of the carves and the production of the dovetails need more time in comparison to perforated plates with similar characteristics. When assembling dovetails, it is necessary to work precisely, which also has a negative influence on the cost-efficiency because it takes time.

Dovetails can only be used partly inside a wall, because if levelling of the module is necessary, the distance between the modules is extended and the dovetail cannot be placed into the cut-outs anymore. Dovetails, that are located inside the ceiling do not affect the levelling of a floor as the connection does not influence the adjustment of the level. A positive aspect of using wooden dovetails is the sustainability of the material compared to metal connectors.

Figure 20: Modular timber construction with dovetail joints

6.2.5 Mortise and Tenon

Static Properties:

Mortise and Tenon connections can absorb horizontal shear forces and are holding the modules in the correct position (Bundesbildungszentrum des Zimmerer- und Ausbaugewerbes, n.d.; SAINT GOBAIN Brüggemann Holzbau GmbH, 2023). From the static properties point of view, the tenon for this connection technique can also be designed as a metal tenon.

Structural Properties:

On the construction site, the tenons can be inserted into the ceiling of the modules and the next one is placed on top afterwards. The tenon itself can be tapered at the ends. By doing this, it becomes easier to adjust the modules on the tenon and the module is going in the right position automatically. The concept of mortise and tenon is presented in Figure 21. The modules are pulled apart to visualize the connection technique. The assembling of the tenons can done simultaneously to the erection of the modules. Nevertheless, this type of connection requires precise work (SAINT GOBAIN Brüggemann Holzbau GmbH, 2023).

Building Physical Properties:

The tenon can also be used in combination with elastomeric bearings to improve the required sound insulation. If mortise and tenon connections are needed in the exterior wall with the airtight layer, it could lead to problems on the airtightness as the tenon would puncture the foil. Due to the fact that the mortise and tenon connection is placed inside the CLT, it is protected by the timber of the modules. Consequently, this connection technique does not have an impact on the fire resistance of the construction.

Other Characteristics:

Concerning the adjustability between each floor, the mortise and tenon connection may have an influence on this. If one floor needs to be adjusted in level, a short distance in the contact gap can be created due to the length of the tenon. The bigger the extension of the contact gap, the more difficult it gets the tenon into the mortises. Due to the fact that a mortise and tenon connection is a stacking system, it leads to a higher pace of assembling and to a cost-efficient connection. A stacking system is also easy to deconstruct because it does not need fasteners which also increases the sustainability because it causes less damage during deconstruction and improves the circular economics.

Figure 21: Exploded assembly drawing of modular timber construction using mortise and tenon

6.2.6 Mortise and Tenon with Fastener

Static Properties:

The mortise and tenon connection can additionally be connected with a fastener such as a screw or a bolt. In this case, the special connection can absorb tension forces. This is the only difference to normal mortise and tenon connection and all other properties are the same (Bundesbildungszentrum des Zimmerer- und Ausbaugewerbes, n.d.).

Structural Properties:

These joints needs to be applied precisely to get the fastener in the right position of the tenon. Depending on the degree of prefabrication a fastener can be adjusted from the inside of the of the wall into the tenon. The higher degree of prefabrication, the more difficult it gets to screw into the fastener. Another possibility is to screw into the tenon from outside of the module but in some cases, other modules are already set up on the side and it is not possible to connect the module with the tenon. The only difference is that the connection can absorb tension forces.

Other Characteristics:

If a mortise and tenon connection is used to absorb tension forces, the cost-efficiency decreases. The reason is that the number of forces that can be absorbed is lower compared to tension rods or perforated plates and it takes more time to screw the fasteners through the wall into the mortise and tenon connection. This system is less deconstructable because it is difficult to get all fasteners out of the mortise and tenon connection. In regards to the sustainability, the mortise and tenon connection is good because a low amount of timber or steel is needed and the process of preparation does not take a lot of machine working time.

6.3 Screws

Static Properties:

Metal screws are available in different strenghts and can be used for shear forces and also for tension forces.

Structural Properties:

For connceting stacked modules, screws are put in from above through the bottom into the ceiling of the module below. By screwing in an angle of 45 degrees crosswise, the screws are laoded in tension forces and absorb the horizontal shear forces in between the contact gap. By screwing in a right angle, the screws can also absorb uplift forces. In this case, the screws are also loaded in tension forces. The problem of using screws as a fastener is the degree of prefabrication. It is only possbile to use this type of fastener if the screed and the impact sound insulation are not laid in the modular timber construction at the moment of assembling (Kreyenschmidt, 2023).

Building Physical Properties:

The screws do not influence the fire resistance as they are protected by timber. The sound insulation can be improved by using elastomeric bearing in the contact gap of the stacked modules. Because of the postion of the screws, the airtighlayer is not affected.

Other Characteristics:

In regard to the time and also to the cost-efficiency to screw the amount of screws into the wood takes time, compared to stacking systems and decreases the efficency. An adjustment of the level on each floor with compensation plates can be created by using screws. As the contact gap gets bigger, it can be possible the screws are to short and therefore the strength of the concetion is reduced. Changing the length of the screw can solve this problem. In terms of levelling, the contact gap is expended, which leads to the problem, that the scwres are bended and could fail under static conditions, as a moment is created. If a low degree of prefabrication allows to use screws as a fastener, it is a cost-efficient connection technique because no preparation is needed and by changing the amount of screws, the number of forces can be absorbed. The screwing can be done during or after the assambly, which leads to a high pace of erection and a lower waiting time for the crane. Since the screws are located under the screed and the impact sound insulation, deconstruction is more difficult.

6.4 Rod

Static Properties:

Steel rods can be classified as special connection for uplift forces, as they are capable to bear tension forces. The rods are placed vertically through the wall of the module and absorb the tension forces in vertical direction. By connecting the rods of each module to a longer rod, the building is secured against uplift on the heigh of the building forces. The concept of tension rods and their exact position inside the walls of modular timber constructions is shown in Figure 22 (Stora Enso, 2016).

Structural Properties:

Problems, which can occur when using rods to connect two modules are the long holes in the CLT, which are necessary to attach the fastener. Precise work is needed to bring the rod in the exact direction. As very long drill needs to be used to drill through the wall, it is possible that the drill does not go perfectly straight when drilling. Consequently it can be difficult to insert the rod afterwards, so that the modules cannot be connected (Kekki, 2022). Another method of preparing the spot for the applying of the tension rod is to mill a slot on the outside of the wall. This can be done with the help of a CNC-technology. After or during the assembly of the modular timber construction, the tension rod can be inserted into the slot from the side or from above (Kreyenschmidt, 2023).

Building Physical Properties:

Since the rod connection is placed inside the CLT, it is protected by the wood of the modules. Therefore, this connection technique does not affect the fire resistance of the modular timber construction. If tension rods are needed in the exterior wall where the airtight layer is created, it could lead to problems on the airtightness, because the rod could puncture the foil.

Other Characteristics:

As the holes, where the rod is inserted, need to be drilled precisely, it can be difficult to level the modules afterwards. The distance that needs to be adjusted is significant, because it is only possible to make small changes, to ensure that the rod of the module on the bottom and the rod of the one on top can really be in line. Otherwise a proper connection of the rods is not possible.

Since the tension rod is as long as the height of the modules, a high amount of steel is needed which decreases the sustainability of this connection technique. After assembly, the rod is in tension, but because of the shrinkage properties of wood, the tension can fade over time (Kekki, 2022). The connection between the rods in vertical direction of each module needs to be finished after the tension rod is inserted and connected. Connecting the tension rods could lead to difficulties because the rod is inside the wall. In addition to that, the position of the connection leads to difficulties during deconstruction because it is not accessible.

6.5 Steel Plate Joints

6.5.1 Perforated Plate

Static Properties:

Perforated plates can be used to absorb horizontal and vertical shear forces as well as tension or pressure forces in the ceiling slice. They can also be applied as a special connection to carry uplift forces.

Structural Properties:

Perforated plates do not require any preparation. During the erection of modular timber construction, the perforated plate is applied on the modules by using nails or screws. Through the number of nails or screws, it takes more time to connect the modules to each other. Another challenge is the vertical connection shear transfer as shown in Figure 22. When the first modules are in the right position, the next module cannot get any vertical connection shear transfer, because it is not possible to secure the perforated plate (Kekki, 2022).

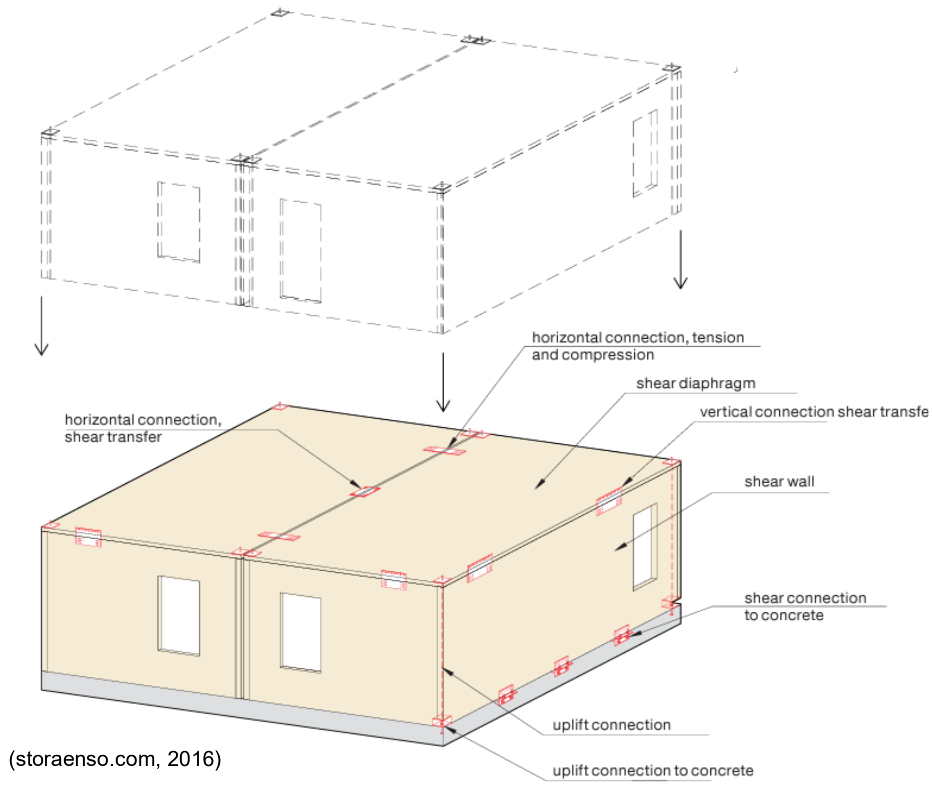
Building Physical Properties:

If necessary, the sound insulation requirements can be improved by using elastomeric bearings in the contact area between the perforated plate and the timber.

In case of fire, the perforated sheets in the area of the stacked modules, are shielded by the wood. In the joint between the adjacent modules, the perforated plate must be protected from heat by using materials such as rock wool. It should also be taken into consideration, that steel loses its strength, when exposed to fire. Since the perforated plates are thin and do have a large surface, they are heated up faster than other connectors, which have a higher mass.

Other Characteristics:

In the case that a floor needs to be levelled, perforated plates have no influence on it because the plates are able to span the higher distances due to the adjustment in between the modules. Perforated plates are ranked as a cost-efficient fastener because they can carry many cases of acting forces. Another positive aspect concerning the cost-efficiency is that no preparation is needed. In order to maintain the possibility of deconstruction, perforated plates have a disadvantage compared to form-fit connections. Due to screws and nails as force-locking connections, it is problematic to remove these when it comes to deconstruction. Alternatively, the perforated plate can be cut for deconstruction which does not affect the rest of the modular timber construction.



(storaenso.com, 2016)

Figure 22: Modular timber construction with perforated plates and tension rod

6.5.2 Hooked Plate

Static Properties:

Hooked plates have small nails all over the surface to connect components, panelised construction or modular timber construction. This fastener can absorb horizontal shear forces in contact gaps of stacked modules.

Structural Properties:

The hooked plates can be attached to the modules beforehand. The next module is placed on the ceiling and the nails are pressed into the CLT. This connection cannot absorb tension forces, so that dismantling is possible (Rothoblaas, n.d.c).

Building Physical Properties:

Since the hooks of the hooked plate must be completely pressed into the wood, the use of additional elastomeric bearings is not possible. Therefore, the improvement of the sound insulation by using elastomeric bearings is not possible (SAINT GOBAIN Brüggemann Holzbau GmbH, 2023).

Other Characteristics:

The use of hook plates can lead to problems if the hooks do not completely go into the wood due to the mass of the modular wooden construction. In this case, it is difficult to press the hook plate into the wood afterwards. Hook plates are more expensive than cleats, as metal fasteners are more expensive than wood pieces. This results in higher costs for the fastener, which influences the cost-efficiency negatively. Hook plates are also less sustainable due to the material. The use of hook connectors in the exterior wall could puncture the foil of the airtight layer depending on the chosen construction type of the module. If it is necessary to modify the level of a floor, problems can occur. Through the higher distance in the contact gap of two stacked modules, the hooks of the hooked plate are not completely inside the timber anymore and the strength of the hooked plated decreases.

Figure 23: Hooked plates

6.6 Brackets

6.6.1 Angles

Static Properties:

Angles are steel brackets which can absorb horizontal shear forces and tension loads. They can be used for wood-concrete joints and for wood-wood joints (Rothoblaas, n.d.d). If necessary, angles with higher strength properties need to be produced for the concept of modular timber construction, which is demonstrated in Figure 24. These angles need to be improved for the case of bending in the corner of the angle bracket to absorb the shear forces in the horizontal slice.

Additionally, angles like in Figure 24 can be produced for corners of modular timber construction. These angle brackets have higher strength due to the design.

Structural Properties:

Angles can be applied at the edge of the ceiling. Then the upper module can be placed onto the ceiling. Due to angles at the edges, the upper module is secured in the right position, as it is shown in Figure 24. If the angles are dimensioned correctly, it is possible to transmit the horizontal shear forces via the pressure between the module and the angles. Without the use of screws or nails in the angles, this construction is similar to a stacking system which saves time during assembly. After each floor is erected, it is possible to create the ceiling slice with other fasteners such as perforated plates or dovetail joints.

Another option would be to develop angles for corners such as the ones which are illustrated in Figure 25. A characteristic of these angles is that they are wider at the top to form a funnel. This funnel makes it easier to get the module in the right position. The angles are produced to absorb the horizontal shear forces via the pressure between the module and the angles. If the construction has problems with uplift, it is possible to attach the angles to the upper module. In this way, the angles can support the tension loads (Kekki, 2022).

If the angles are not strong enough to absorb horizontal shear forces, screws can be added to transmit the forces from the angles to the module below. Consequently, the modules do not work as a stacking system anymore and therefore it is difficult to apply screws in the angles between two rowed modules. The screws also lead to problems concerning deconstructability and this decreases the sustainability of the modular timber construction because the building materials can be damaged during deconstruction. Thus it can be problematic to reuse the materials. In the table in the end of this thesis the connection technique is compared without the additional screws for absorbing horizontal shear forces.

Building Physical Properties:

By using elastomeric bearings in combination with angles, structural noise bridges are reduced and the sound insulation is improved. If angles are needed at the exterior wall with the airtight layer, it could lead to problems on the airtightness (SAINT GOBAIN Brüggemann Holzbau GmbH, 2023). Due to fire resistance issues, the steel connectors must be protected from heat. The reason is that the steel angles will lose strength quickly when they get hot.

Other Characteristics:

The following Figure 25 shows an angle bracket which can be applied in corners of a modular timber construction. This angle is designed to combine the fastener and if necessary, a tool so that it can be attached to the crane. By using corner brackets, the position is applied in any horizontal direction. Due to the shape, the module is moved into the correct position by itself and since the upper part is wider, the manoeuvring of the module is simplified. The hole for attaching the module to the crane can be used to connect the stacked modules by screws as well. In this case it works as a special connection for carrying uplift forces (Kekki, 2022).

If these angles are used to move the module by crane, they have to be attached to the module beforehand to transfer the module on the trailer. This can be a problem for transportation, because the module is taller than without the angles and transport regulation can be exceeded. If the brackets are not used for moving the modules by crane, the brackets can be attached to the module on the construction site (Kekki, 2022).

In the case, that the level of a floor needs to be adjusted is can lead to static problems in the angle bracket of the lower module. Due to the modified height between the stacked modules and due to the horizontal shear forces in this contact gap, a moment is created and the angles could fail.

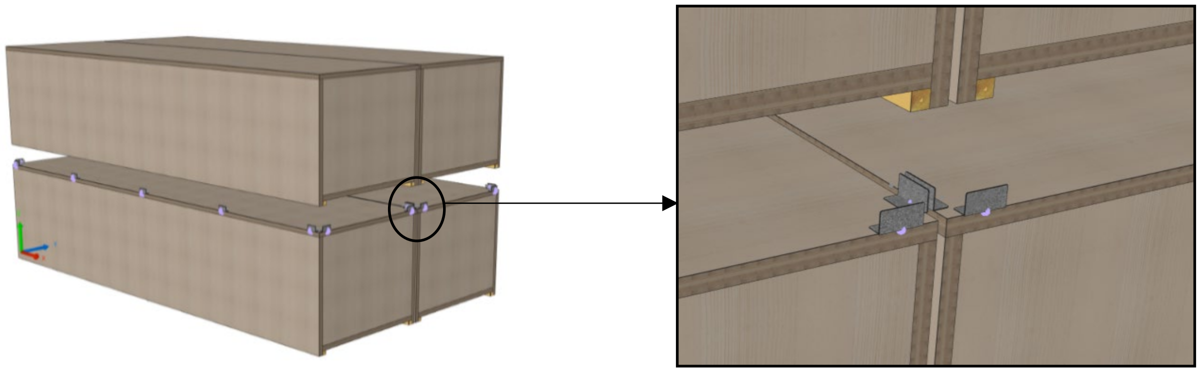


Figure 24: Modular timber construction using angles

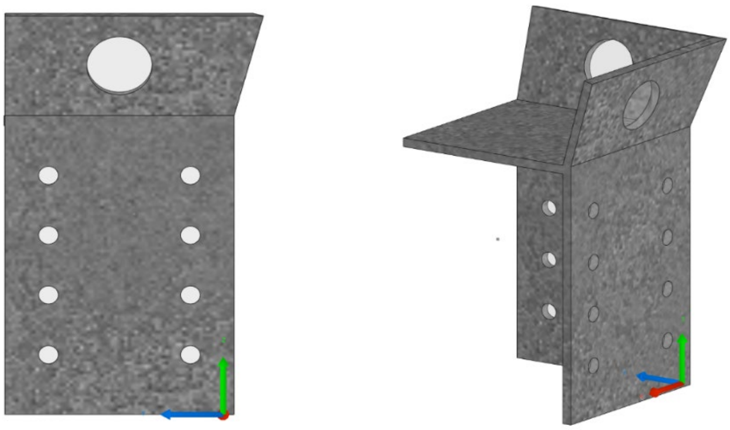


Figure 25: Angle for modular timber construction

6.6.1 Hook connector – Beam Joints

Static Properties:

Beam joints can absorb forces vertical shear forces, horizontal pressure forces and horizontal tension forces between rowed modules. The uplift forces in this system are carried by connecting the two individual parts of the fastener with screws. This detail can be seen in Figure 26. For horizontal shear forces in the horizontal slice, other fasteners or connection techniques are necessary (Rothoblaas, n.d.a).

Structural Properties:

With the help of hook connectors, a plug-in system can be created by precisely attaching the two elements of the hook connector to the modules. To simplify this system, the hook connectors should only be applied on the top or bottom of the walls. To connect the modules, wooden spacers are additionally needed on the top or bottom of the same wall. Due to the wooden spaces the assembling is simplified, because there are less form-fit connections and the wooden spacers are holding the correct distance to the next module. This concept is presented in Figure 26 where the sideview of the modular timer construction demonstrates the use of the beam hangers on the top of the wall and wood pieces on the bottom of the wall. Consequently, it is possible to achieve the same distance between the modules. The front side of the modules can be connected in the same way.

Beam hangers are form-fit fasteners and have no deviation, which makes them difficult to use in this application. This is even harder when components with more than one beam hanger are to be plugged together. In order to ensure the accuracy, the positions should be marked on the walls by using CNC-technology. Beam hangers with more clearance should be used to facilitate the assembly. Because a stacking system is used, a high pace of erection can be achieved, even though precise work is required. (Fritz Kathe & Sohn GmbH, 2023; SAINT GOBAIN Brüggemann Holzbau GmbH, 2023).

Building Physical Properties:

Due to the fact that this fastener is used between the walls of a module it has no impact on the airtight layer of a building. The material also does not affect the fire resistance of the building as the aluminium that is used for the connector is classified in A1 of fire resistance rating (Rothoblaas, n.d.a).

Other Characteristics:

Beam Joints are easy to remove which leads to positive aspects if deconstructing the building is taken into consideration. The deconstructability also improves the sustainability of the building (Fritz Kathe & Sohn GmbH, 2023). The beam joint exists only between the lined up modules and does not affect the level adjustment. Beam hangers itself are more expensive that fasteners with similar strength like perforated plates but due to the stacking system the cost-efficiency is ranked as neutral.

(rothoblaas.com, n.d.)

Figure 26: Hook connector - beam joints

Figure 27: Modular timber construction using the hook connector

6.6.2 Hook Connector – Joint Profile

Static Properties:

The joint profile consists of aluminium hang-in profiles, which are loaded in vertical direction. For vertical shear forces between rowed modules, the connection can be secured either with screws or with angles on the side of the profile. Both options are illustrated in Figure 28 to clarify how shear forces can be absorbed. On the left hand side of the figure the screwed option for carrying shear forces is presented and on the right hand side the opportunity of using angles at the end of the joint profile is shown. By using the first technique, where the screws are applied through the profile joint into the modular timber construction, uplift forces can additionally be absorbed. If necessary, both options can be used in combination. Due to the form-fit connection, the fastener can absorb pressure and tension forces in horizontal direction in the ceiling (Rothoblaas, n.d.b). Shear forces in the horizontal slice can only be absorbed by applying an additional fastener or connection technique.

Structural Properties:

The two parts of the connector can be pre-assembled with screws to the modular timber construction. Due to the pre-installed joint profiles, this is a plug-in system. If the shear forces are to be absorbed with angles in the joint profile, this can also be preassembled. If the shear forces are to be taken up by screws, this must be done during the assembly. This connection can be made with a profile on the top and bottom of the wall or with a profile on the top of the wall and pieces of wood at the bottom of the wall, keeping the right The second alternative is easier to join together as it is only necessary to pay attention to one profile than to both profiles

Building Physical Properties:

Profile joints are made of aluminium which is ranked in fire resistance class A1. In order to improve sound insulation, elastomeric bearings can be used in between the joint profile and the timber. Since this fastener is used between the walls of a module, it does not affect the airtight layer of a building.

Other Characteristics:

If the shear forces are absorbed by angles in the joining profiles, this connection technique is a full plug-in system and deconstructable. Additionally, by absorbing the shear forces via screws it is also possible to deconstruct the modules. As a lot of screws are used in spots, that are not easily accessible, the deconstruction is more difficult. The joint profile connection is only used in between rowed modules and does not influence an adjustment of the level. The cost-efficiency of profile joint is ranked as neutral because the high pace of erection through the stacking system is compensated by the higher cost of the profile joint itself compared to similar fasteners such as perforated plates.

Figure 28: Examples of absorbing shear forces with screws or angles

6.6.3 Dowell Joints

Static Properties:

Dowell joints are steel fasteners used for absorbing horizontal shear forces in the contact gap between a module and the module on top (Spax, n.d.).

Structural Properties:

The dowell itself is pressed into the ceiling of the module beforehand and needs no more preparation. What could be challenging about using dowell joints is that they are sometimes not going completely into the wood of the module on top due to their own weight. Due to this fact dowell joints are hard to use (Fritz Kathe & Sohn GmbH, 2023).

Building Physical Properties:

Another challenge could be that elastomeric bearings in combination with the dowell joint cannot be used, as the elastomeric bearing and the modules are not directly on top of each other (SAINT GOBAIN Brüggemann Holzbau GmbH, 2023).

Other Characteristics:

Through the fact that dowell joints cannot absorb tension forces, deconstruction is possible (Spax, n.d.). When it is necessary to modify the level of a floor, this could lead to difficulties. Due to the larger distance in the contact gap of two stacked modules, the hooks of the dowell joints no longer lies completely in the wood of the module and the strength of the dowell joint is reduced.

6.6.4 HCW - Hilti Connector Wood

Static Properties:

The wood connector HCW is a special connector which was developed for prefabricated constructions. The fastener can absorb horizontal shear forces and tension forces by interlocking. As it can be seen in Figure 29, the HCW connector is put onto a hanger bolt. Two clippers inside the HCW connector are locking into the thread of the hanger bolt automatically and ensures the position (Hilti Deutschland AG, 2022).

Structural Properties:

In case of stacking two modular timber constructions, the lower module gets prepared with hanger bolts on the ceiling of the module beforehand. During the positioning of the hanger bolt, precise work is necessary. The module which is placed on top is provided with the fastener HCW. For using this fastener, holes need to be joint on the bottom of the module where the HCW fastener is inserted. On construction site, the module only needs to be put on each other and the system locks automatically (Hilti Deutschland AG, 2022).

Building Physical Properties:

The position of the joint has a positive aspect concerning fire resistance and a negative influence on the airtight layer. Both parts of the connector are protected by the wood, because the HCW is drilled into the wood and the hanger bolt is screwed into the wood.

Through the construction process, the airtight layer could be punctured by the hanger bolt of the connector.

Other Characteristics:

The HCW fastener leads to a high pace of assembling due to the interlocking system. The high pace and the amount of forces which can be absorbed by HCW connectors improve the cost-efficiency. But this interlocking system also leads to problems concerning deconstruction because the interlocking is inside the contact gap of the ceiling of the lower module and the floor of the module on top and is not accessible after interlocking. This also leads to a negative ranking of sustainability because reusing building materials is more challenging, if deconstruction is not possible or difficult. Because of the fact that the hanger bolt has a thread where the HCW fastener gets locked, a nut can be used for adjusting the correct level.

Figure 29: Interlocked hanger bolt in a HCW connector

6.7 Gluing

Static Properties:

Gluing is a chemical technique to connect two materials. It is used for many wooden materials like CLT or OSB plates. This kind of connection could be used for modular timber construction, as a result of its ability to absorbs horizontal shear forces and tension forces. The direction of the fibres also affects the strength of the bonded joint. Parallel to the fibre, the two materials can be bonded together without any further connecting element. If tension loads are applied orthogonally to this joint, the strength properties are lower than tension forces in the longitudinal direction of the fibres. For a bonded joint in the longitudinal direction of the fibres, additional bolts or rods are needed (Kreyenschmidt, 2023; Purgstaller, 2010).

Structural Properties:

Since, many factors influence the bonding process, it is difficult to use and calculate the static strength of the glued connection. When bonding, factors such as time, temperature and humidity must be taken into consideration to achieve the desired strength of the bonded joint. Since the installation of modular timber construction takes place under the influence of weather, it is difficult to ensure the appropriate conditions (Purgstaller, 2010; SAINT GOBAIN Brüggemann Holzbau GmbH, 2023). Additionally, using glued connection a special permit for gluing is necessary (Kreyenschmidt, 2023).

Another method of using glue, is to insert the adhesive after assembling by injection. A two-component glue can be injected from the inside of the modular timber construction into the contact gap parallel to the fibres of the timber of the stacked modules. In this case the time aspect and the influence of weather are not considered anymore, as the gluing process takes place inside the module. The challenging factor using glued connection is to hit the contact gap in between the stacked modules. Also it is only possible to insert the glue, if the degree of prefabrication is lower, to make sure that the contact gap is still accessible and the injection tool can be inserted through the floor or the wall (Kreyenschmidt, 2023).

Building Physical Properties:

A glued connection does not affect the foil of the airtight layer because it cannot puncture the foil or alter the area where the foil is inserted. Glue can lose its strengths when it gets hot, but since the glue is injected in between the stacked modules it is protected by the timber.

Other Characteristics:

The first method, even when assuming that bonded joints are a as reliable connection technique as form-fit connections and force-lockings, they are not as efficient because it takes more time for the glue to dry then to apply a different connector. This decreases the time efficiency and increases the costs. The second method is regardless to the time a does not affect the efficiency by the time aspect.

Inserting the glue in the contact gap does take the same or more time as to apply a different connector. By using a glued connection, it is not possible to deconstruct a building and is less sustainable, because the glue cannot be removed. Bonded connections are applied on a large area and prevent an adjustment of the level between stacked modules. If the foundation is not perfectly straight it leads to problems if glued connections are chosen. Nevertheless, this option is not as efficient, as the degree of prefabrication has to be lower in this case.

7 Parameter of the Comparisons

As a result of the variety of building types, the individual structure of buildings and the different interests of the building owners, a direct comparison of fasteners or connection techniques is not possible. The comparison will not give a ranking, of which fastener is the best one, but investigates which loads can be absorbed and which qualities each technique has. The evaluation is therefore only divided into three levels. It was scrutinized, whether a fastener or joining technique improves the desired parameter, has no effect on it, or decreases the chosen parameter. Due to the fact that every fastener or connection technique has different strengths, different fasteners and connecting technique can be used in combination to connect different modules of a building

The following Table 7 shows the parameters which are taken into account for the comparison. A short explanation is given to distinguish between the different parameters:

Table 7: Parameters for the comparison of fasteners and connection techniques

Absorption of horizontal shear forces	+	can absorb horizontal shear forces
	O	no impact
	-	
Absorption of vertical shear forces	+	can absorb vertical shear forces
	O	no impact
	-	
Absorption of uplift forces	+	can absorb uplift forces
	O	no impact
	-	
Absorption of horizontal pressure forces	+	can absorb horizontal pressure forces
	O	no impact
	-	
Absorption of horizontal tension forces	+	can absorb horizontal tension forces
	O	no impact
	-	
Complexity in preparation	+	no preparation needed
	O	
	-	high degree of preparation needed

Transport	+	
	o	no impact
	-	has an impact on the transportation regulations
Moving by crane	+	connector can be used to move the module by crane
	o	no impact
	-	connector cannot be used to move the module by crane
Speed of erection	+	quick erection
	o	no impact
	-	takes more time for erection
Accessibility during assembly	+	good accessibility during assembly
	o	no impact
	-	bad accessibility during assembly
Difficulties during installation	+	
	o	no impact
	-	very likely that difficulties occur during erection
Adjustability	+	no impact on the levelling
	o	has an impact on the levelling, but is still possible
	-	not possible to adjust the level
Usability depending on degree of prefabrication	+	can be used in a high degree of prefabrication
	o	no impact
	-	parts of the module need to be finished after erection
Deconstruct ability	+	joint is able to be deconstructed
	o	no impact
	-	it is difficult to deconstruct the joint
Cost-efficiency	+	increases the cost-efficiency
	o	no impact
	-	decreases the cost-efficiency
Sustainability	+	sustainable material
	o	no impact
	-	less sustainable material
Sound insulation	+	good sound insulation
	o	can be used with impact sound insulation material
	-	cannot be used with impact sound insulation material
Fire resistance	+	highly fire resistant or protected by wood
	o	
	-	needs to be protected against heat
Airtightness	+	
	o	no impact
	-	can lead to problems on the airtight layer
	\	Not taken into account

8 Table: Parameter - Fastener or Connection technique

Table 8: Table of parameters with regard to the fasteners and connection techniques

	Elastomeric Bearing “Speba”	Elastomeric Bearing “Phonestar Schalll”	Elastomeric Bearing Cork	Elastomeric Bearing “Xylophone”	Friction	Cleat	Wooden Lug	Dovetail Joint used in ceilings
Absorption of horizontal shear forces	+	+	+	+		+	O	O
Absorption of vertical shear forces	O	O	O	O		O	+	+
Absorption of uplift forces	O	O	O	O		O	O	O
Absorption horizontal pressure forces	O	O	O	O		O	+	+
Absorption horizontal tension forces	O	O	O	O		O	+	+
Complexity in preparation	+	+	+	+		O	O	-
Transport	O	O	O	O		O	O	O
Moving by crane	O	O	O	O		O	O	O
Speed of erection	+	+	+	+		+	+	O
Accessibility during assembly	+	+	+	+		+	+	O
Difficulties during installation	+	+	+	+		-	O	O
Adjustability	+	+	+	+		O	+	+
Usability depending on degree of prefabrication	+	+	+	+		+	+	+
cost-efficiency	+	+	+	+		+	+	-
Deconstructability	+	+	+	+		+	+	+
Sustainability	-	+	+	-		+	+	+
Sound insulation	+	+	+	+		O	O	O
Fire resistance	+	+	-	+		+	O	O
Airtightness	o	o	o	o		-	+	+

	Dovetail used in walls	Mortise and Tenon	Mortise and Tenon with fastener	Screws	Rod	Perforated Plate used in ceilings	Perforated Plate used in walls	Hooked Plate
Absorption of horizontal shear forces	+	+	+	+	O	O	+	+
Absorption of vertical shear forces	O	O	O	O	O	+	O	O
Absorption of uplift forces	+	O	+	+	+	O	+	O
Absorption horizontal pressure forces	O	O	O	O	O	+	O	O
Absorption horizontal tension forces	O	O	O	O	O	+	O	O
Complexity in preparation	-	O	O	+	-	+	+	+
Transport	O	O	O	O	O	O	O	O
Moving by crane	O	O	O	O	O	O	O	O
Speed of erection	-	+	+	O	-	-	-	+
Accessibility during assembly	-	+	-	+	-	+	-	+
Difficulties during installation	-	O	-	+	-	+	-	-
Adjustability	-	O	O	O	O	+	+	-
Usability depending on degree of prefabrication	-	+	-	-	-	+	-	+
Cost-efficiency	-	+	-	+	-	+	+	-
Deconstructability	+	+	-	-	-	+	+	+
Sustainability	+	+	+	-	-	-	-	-
Sound insulation	O	O	O	O	O	O	O	-
Fire resistance	+	+	+	+	+	-	-	+
Airtightness	-	-	-	+	-	+	-	-

	Angle	Angles for corners	Beam Joint	Joint Profile	Dowell Joint	HCW	Glue	
Absorption of horizontal shear forces	+	+	O	O	+	+	+	
Absorption of vertical shear forces	O	O	+	+	O	O	O	
Absorption of uplift forces	O	+	+	+	O	+	+	
Absorption horizontal pressure forces	O	O	+	+	O	O	O	
Absorption horizontal tension forces	O	O	+	+	O	O	O	
Complexity in preparation	O	O	-	O	+	-	-	
Transport	O	O	O	O	O	O	O	
Moving by crane	O	+	O	O	O	O	O	
Speed of erection	+	+	+	+	+	+	-	
Accessibility during assembly	+	+	+	+	+	+	-	
Difficulties during installation	+	+	-	-	-	+	-	
Adjustability	O	O	+	+	-	+	-	
Usability depending on degree of prefabrication	+	+	+	+	+	+	O	
Cost-efficiency	+	+	O	O	+	+	-	
Deconstructability	+	+	+	+	+	-	-	
Sustainability	+	+	+	+	+	-	-	
Sound insulation	O	O	O	O	-	O	O	
Fire resistance	-	-	+	+	+	+	+	
Airtightness	-	-	+	+	-	-	+	

9 Conclusion

This research aimed to compare different fasteners and connection techniques in modular timber construction. Based on manufacturer data, reference books, internet research and personal conversations, this topic was investigated. For this purpose, possible fasteners and existing concepts were collected, as well as own concept ideas were developed. Most fasteners and connection techniques originate from other application areas and as suggested in the introduction, it was very difficult to do research on this topic, because there was only a limited amount of information available. As only a few companies in Germany offer modular timber construction as a service, most concepts remain as a trade secret. By analysing manufacturer data, this thesis has shown how different connection techniques can be and how many specific factors have to be taken into consideration before deciding on a fastener. With a focus on the complexity of buildings, a direct comparison is difficult so that the fasteners and connection techniques were only examined to determine which properties they have. Because of this, the concepts were discussed with timber construction experts. It became clear that each fastener and each connection technique has advantages and disadvantages and therefore, the general properties have to be considered. In order to find usable solutions, several fasteners should be combined, for one building to make use of their individual qualities.

Stacking systems in particular are suitable for increasing the speed of construction and therefore are meeting the rapid demand for buildings as already indicated in the introduction. The concepts, that were discussed in this bachelor thesis, can be used to further develop modular timber construction and to fill the lack of information concerning this area of construction. For example, the creation of a static model calculation would show whether these concepts can be implemented. In particular, the topic of friction should be revised in Germany. By absorbing shear forces through friction, modular construction can make progress and become more attractive.

With an eye on the available information and the small number of companies in the modular timber construction sector, companies should consider to work together with universities, experts and other companies to advance modular timber construction and to profit from their experience and knowledge. Additionally, more research needs to be done to make modular timber construction more competitive and future proof.

Through the work on my bachelor thesis, I gained a deep insight into modular timber construction. From my point of view, the degree of prefabrication is remarkable for modular timber construction. Furthermore, due to the use of stacking systems, processes in modular timber construction can be done in a higher pace and deconstructability is possible. This results in a positive aspect on sustainability as materials are reusable and circular economics are improved.

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