

Optimizing Connections for the Reuse of CLT Elements

Master's thesis in the Master's Programme Structural Engineering and Building Technology

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover:
Illustration of different failure modes for a CLT wall-to-floor connection.
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ABSTRACT

The construction and real estate sector significantly contributes to greenhouse gas emissions and waste generation in Sweden. Replacing heavy CO₂-emitting materials like concrete and steel with alternative wood-based products like cross-laminated timber (CLT) can be an effective measure. However, this will result in higher demand for timber, which may increase the challenge in maintaining sustainable forestry. By designing its connections with reuse in mind, a CLT panel could be used in multiple iterations, mitigating the demand and prolonging carbon storage. The objective is to provide overall guidelines for design when reusability is to be considered. To develop an effective connection for the reuse of the CLT panel, interviews were conducted with respondents from the construction industry, and insights regarding reusability and its practical application were gained. Furthermore, a parametric study was performed to find how different connection configurations affect the governing failure mode. The connection type and kind of fastener were found to have the greatest impact on reusability. Screws with larger diameter in a bracket configuration is preferable compared to long construction screws and nails if reuse of the CLT panel is intended. Moreover, to ease disassembly, the connection must be designed to fail in the bracket and not in the timber or the fasteners. From the parametric study it was found that the aspect of rope effect in screws have a large impact on governing failure modes in some cases, highlighting the importance of its consideration. With this knowledge, a genetic algorithm (GA) was constructed to obtain optimized connections, with regard to cost and reusability.

Key words: Failure Mode, Cross-Laminated Timber, Reusability, Genetic Algorithm, Timber Connections

Optimera Anslutningar för Återanvändning av KL Element

Examensarbete inom masterprogrammet Konstruktionsteknik och Byggnadsteknologi

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SAMMANFATTNING

Bygg- och fastighetssektorn står för en stor del av utsläppen av växthusgaser och avfallsgenereringen i Sverige. Att ersätta material med höga CO₂-utsläpp, såsom betong och stål, med alternativa träbaserade produkter som korslimmat (KL) trä kan vara en effektiv åtgärd. Men när efterfrågan på trä ökar så kan det försvåra möjligheten till ett hållbart skogsbruk. Genom att utforma kopplingarna med återbruk i åtanke kan en KL-panel användas i flera iterationer och därmed mildra efterfrågan samtidigt som det förlänger kollagringen. Syftet är att ge designriktlinjer för när återbruk skall beaktas. För att utveckla en effektivt koppling som tillåter återbruk av KL panelen så genomfördes intervjuer med respondenter från byggbranschen, och insikter om återbruk och dess praktiska tillämpning erhöles. Vidare genomfördes en parametrisk studie för att undersöka hur olika kopplingskonfigurationer påverkar den dimensionerande brottmoden. Typ av koppling och förbindare visade sig ha störst inverkan på återbrukbarheten. Vinkeljärn tillsammans med skruvar med större diameter är att föredra framför långa konstruktionsskruvar och spikar om KL-panelen avses att återanvändas. För att underlätta demontering, måste kopplingen utformas så brott sker i vinkeljärnet och inte i träet eller förbindaren. Av den parametriska studien så konstaterades det att aspekten av linverkan i skruvar har stor inverkan på dimensionerande brottmoder i vissa fall, vilket visar på vikten av att ta hänsyn till den. Med denna kunskap konstruerades en genetisk algoritm (GA) för att erhålla optimerade kopplingar med hänsyn till kostnad och återbruk.

Nyckelord: Brottmod, Korslimmat trä, Återbruk, Genetisk algoritm

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Preface

This thesis was carried out between January and June of 2025 at Chalmers University of Technology, Division of Structural Engineering, in collaboration with PE Teknik & Arkitektur.

First of all, we would like to thank our supervisors at Chalmers, Vera and Zhengyao, for sharing their knowledge and supporting us throughout the project. We also want to thank our examiner, Mohammad, for guiding our choice of methods.

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We have also appreciated the helpful feedback and enjoyable discussions with our opponents, Alice and Karin, during our regular meetings.

Lastly, to our significant others, we want to send our greatest thanks for the support along the way. Thanks for the patience and encouragement. Now let us enjoy our travels.

Gothenburg, June 2025
Alex Drabczyk Nylander
Erik Elmäng

Notations

Roman upper case letters

A_v	Shear area of steel bracket
B	Width of steel bracket
B_{limit}	Maximum width of steel bracket used in the GA
B/P_{ratio}	Maximum width to depth ratio of steel bracket used in the GA
CLT	Cross Laminated Timber
CO ₂ e	Carbon dioxide equivalents
DEI	Dissassembly Effort Index
DfD	Design for disassembly
DfR	Design for reuse
EoL	End-of-life
EYM	European yield model
F_{ax}	Anchorage capacity of the fastener
F_{RK}	Illustrative capacity
F_w	Resulting characteristic shear force from several floors
$F_{w,d}$	Resulting design shear force from several floors
$F_{w,i}$	Resulting characteristic wind load on one wall on one floor
GA	Genetic algorithm
GHG	Greenhouse gas emissions
H	Height of steel bracket
L	Longitudinal direction of a CLT element
M_y	Yield moment of the fastener
N	Total number of fasteners in a connection
P	Depth of steel bracket
$R_{k,d}$	Characteristic load-bearing capacity of the ductile element
$R_{k,e}$	Characteristic load-bearing capacity of the non-ductile element
S	Thickness of steel bracket
SEK	Swedish kronor
T	Transversal direction of a CLT element

Roman lower case letters

d	Outer diameter of the threaded part of the screw
d_{ef}	Effective diameter of the screw
d_h	Diameter of the screw head
d_s	Screw shank diameter
d_0	Hole diameter of steel bracket
d_1	Inner diameter of the threaded part of the screw
e_1	Edge distance from the holes in the steel bracket aligned with the direction of the load
e_2	Edge distance from the holes in the steel bracket aligned perpendicular to the direction of the load
f_h	Embedding strength of the timber
f_u	Characteristic tensile strength
f_y	Characteristic yield strength
l	Screw length
l_{ef}	Penetration length of the threaded part of the screw
n	Number of fasteners in a row
n_{ef}	Effective number of fasteners in a row
p_1	Spacing between holes in the steel bracket aligned with the direction of the load
p_2	Spacing between holes in the steel bracket aligned perpendicular to the direction of the load
q_{kx}	Characteristic wind load on the short side of a building
q_{ky}	Characteristic wind load on the long side of a building
$t_{bracket}$	Bracket thickness used in the GA
t_{CLT}	CLT thickness used in the GA
t_{steel}	Thickness of the steel plate / bracket
t_x	Xylomer thickness
w	Deformation
x	Set of design parameters for the GA

Greek upper case letters

ΔF_{Rope}	Capacity increase of a connection due to rope effect
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Greek lower case letters

α	Angle of the load in relation to the grain
γ_{Rd}	Overstrength factor
ρ_k	Characteristic density of wood

1 Introduction

1.1 Background

The construction and real estate industry has a significant impact on greenhouse gas (GHG) emissions, with the sector contributing to 22% of Sweden's total emissions in the year 2021 and generating 39% of Sweden's total waste in 2022 (Boverket, 2024b). According to the roadmap established by Fossilfritt Sverige, the industry strives to reduce its GHG emissions by 75% between 2015 and 2040 and be net-zero by 2045. This aligns with the European Union's goal of being a net-zero economy by 2050 (European council, 2024). Between the years 1993 and 2022, the construction and real estate industry has made some progress in lowering its domestic emissions, reducing it from 21500 tonnes of carbon dioxide equivalents (CO₂e) in 1993 to about 11000 tonnes (Boverket, 2025). However, this reduction is solely due to reduced emissions from the heating of buildings, meaning that the construction and renovation of buildings still emit roughly the same amount of CO₂e. To tackle this, new approaches must be established.

Fossilfritt Sverige (2024) shows that a key concept to reaching this goal is developing new ways of building, leaving linear design methods behind, and having a more circular approach. Even though there is an increasing interest in reuse in the industry, only a fraction of construction materials is reused in general (Boverket, 2024a). However, reuse is already taking place in smaller pilot projects, and it can be seen that the potential for reuse is high and will contribute to less use of virgin materials.

To further reduce the amount of CO₂e emitted, substituting construction materials like concrete and steel with alternative wood-based products like CLT can be an effective solution (Younis & Dodoo, 2022). For example, by replacing the concrete exterior walls in apartment buildings with equivalent CLT walls, GHG emissions can be reduced by up to 45% (Shin et al., 2023). CLT is used to some extent today, and the market will increase over the following years (Research & Markets, 2024). At the same time, there is an increasing need for timber in other industries, such as the energy sectors (Pohjanmies et al., 2017). This will, in turn, lead to an increased demand for raw timber material, potentially driving up the prices for timber and/or exploiting more land for forestry, while at the same time making sustainable forestry challenging. Therefore, it is interesting to study the reuse of the CLT elements as this could lower the emissions from a timber building substantially.

1.2 Aim and Objectives

This master's thesis aimed to analyze the structural performance and reusability of CLT panels with a focus on their connections, including assessments of strength and ease of disassembly. The study investigated how different failure modes and connection designs influence the potential for reuse after disassembly. The goal was to provide guidelines for designing structurally robust connections that facilitate the reuse of CLT panels.

To achieve this aim, the following research questions will be answered:

- What are the key factors affecting the reusability of CLT elements?
 - How do different failure modes - specifically, failures in the timber, steel brackets, or fasteners - affect the potential for reuse?
- How do different combinations of fasteners and brackets influence failure modes in CLT connections?
- How can CLT connections be optimized for cost and reusability through design modifications?

1.3 Overview of methodology

This report has used different methods, beginning with a literature review on various types of timber connections, failure modes, and theories of disassembly and reuse. In addition, interviews were conducted with representatives from different parts of the construction industry to gather practical insights into CLT, mechanical connections, and methods of assembly and disassembly. These findings provided the basis for the selection of what steel connectors to study. The chosen connectors were then analyzed analytically by using the European standards, EN Eurocodes (2002), to identify potential failure modes. A parametric study was conducted to assess the impact of different design configurations on both structural strength and reusability. Based on the findings from the interviews and the analytical investigation, a GA was developed to optimize connection configurations for cost and reusability. Finally, with the knowledge gained, design recommendations were developed, which facilitate the ease of disassembly of a connection and the reuse of the CLT element.

1.4 Limitations in the study

This thesis focused on the steel connectors between a CLT wall and floor slab. More specifically, the focus was on one shear angle bracket. The CLT timber elements were only studied based on their performance regarding the connection capacity, i.e., it were not investigated how the CLT element itself is affected by long-term effects and its impact on the reusability of it. The analysis was only performed analytically; no experimental tests or finite element modeling was performed.

2 Theory

This chapter aims to provide the necessary theory needed to carry out this thesis. Philosophies regarding disassembly and reuse are explored. Cross-laminated timber is explained regarding its properties and its usage in buildings. Furthermore, various timber connections and methods of disassembly are stated, along with different failure modes. Lastly, the ductile behavior of timber and steel is discussed.

2.1 Design for disassembly and reuse

Design for disassembly (DfD) is a design approach where a product is constructed in a way that allows for easy and time- and cost-effective dismantling of the product into its different components, which in turn can be reused, recycled, incinerated, or disposed (Abuzied et al., 2020). This is done through the early planning and design of the product and acts as a good strategy to reduce the amount of raw material used (Rios et al., 2015). Originally an approach developed in the manufacturing industry, DfD's potential has expanded across its origin into the construction industry, where it can be of good use to battle the large generation of waste (Rios et al., 2015). DfD allows for an alternative way of designing, and the following principles can be seen as guidelines when DfD is to be considered (Guy & Ciarimboli, n.d.):

- Use standard components and dimensions to design simple structures
 - Design easily accessible connections that allow for easy handling and safe deconstruction
 - Design connections with ease of disassembly in mind, i.e. use mechanical connections like bolted, screwed and nailed connections instead of chemical bindings and welding.
- Separate mechanical, electrical, and plumbing systems from the structure, allowing for easier access
- Thorough documentation of materials and routines used for deconstruction.

As the producer's responsibility for the end-of-life (EoL) stage of a product has increased, the attention to this approach has grown larger (Guy & Ciarimboli, n.d.). However, due to various reasons, including impracticality imposed by standards, codes, and professional practices, the usage of DfD is minimal today (Rios et al., 2015).

Design for reuse (DfR), on the other hand, is a further development of DfD. Where DfD focuses on being able to dismantle the different parts of a building, DfR takes this a step further and also aims at incorporating the disassembled components into new and alternative settings, either in another building or within the same building (Bertin et al., 2022). This design philosophy is more firmly rooted in the reuse aspect, emphasizing that the components are not only being disassembled but also reused. This places de-

mands on the ability to predict and control damage and performance degradation of the structural element and its connections (Ottenhaus et al., 2023). To allow for the reuse of the structural elements, the connections have to be designed to allow for assembly, disassembly, and reassembly, all while mitigating the accumulated damage of the members. This can be done by designing the members and connections to be entirely in an elastic state during their service life, meaning no or little yielding, permanent deformations, and damage will occur. Furthermore, the connections should be designed with *Potential Ductile Elements*. A common way to facilitate this is to allow some damage in designated components. This could, for example, be a part of a structural joint that is designed to fail before the rest of the joint or element does, known as *fuses*. This way, in case of loads that lead to yielding, the plastic deformation and energy dissipation will happen in the fuse, providing ductility and allowing the element to stay in an elastic state and not incur any damage.

2.2 Cross-Laminated Timber

CLT is a prefabricated structural element that consists of an odd number of layers of cross-laid boards that are glued together (Swedish Wood, 2017). Due to timber being stiffer in the direction along the grains compared to across the grains, the panel is much stiffer in the longitudinal direction, i.e., the main direction, compared to the transversal direction (Ljunggren, 2023). See Figure 2.1 for an illustration of a CLT element. Due to the manufacturing process and the adaptability of timber, the CLT element can take a wide range of shapes and sizes (Swedish Wood, 2017). It can, therefore, constitute, in principle, all parts of a building's structural system, such as walls, floors, and the roof. CLT has a high strength-to-weight ratio, which is good from a transportation, foundation, and montage point of view. It's also highly resistant to fire and has good thermal properties. In addition, due to the flexibility of timber, it can be reshaped even after manufacturing without too much effort, which is good for reusability purposes.

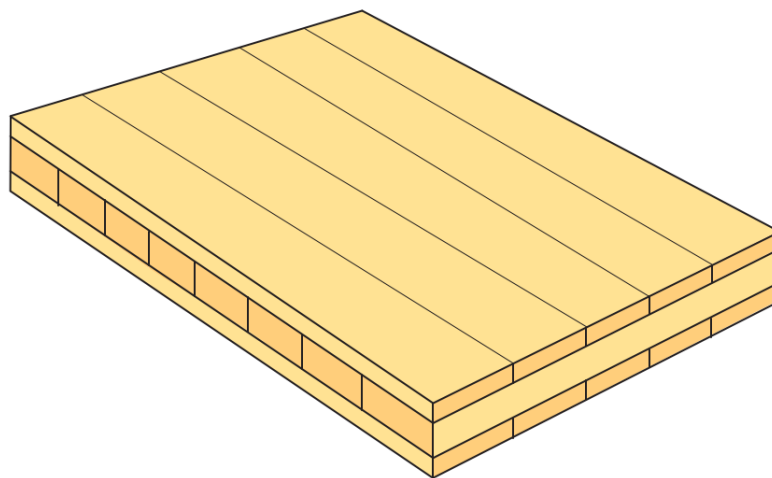


Figure 2.1: CLT panel (Swedish Wood, 2017).

2.2.1 CLT Buildings

A building can be exposed to different kinds of loads, such as wind load, snow load, permanent load, or imposed loads, as can be seen in Figure 2.2. For these loads to be able to be transferred to the foundation in a CLT building, usually the walls and floors are used as stiff panels (Swedish Wood, 2017). The horizontal loads are transferred from the exterior cladding to the floors and finally to the stabilizing wall panels, as can be seen in Figure 2.3a. The wall panels then transfer the load to the foundation by diaphragm action. The vertical loads act on the wall or roof panels and are transferred to the supports, i.e., the CLT walls, as can be seen in Figure 2.3b. The vertical load is then directly transferred to the foundation through the vertical walls.

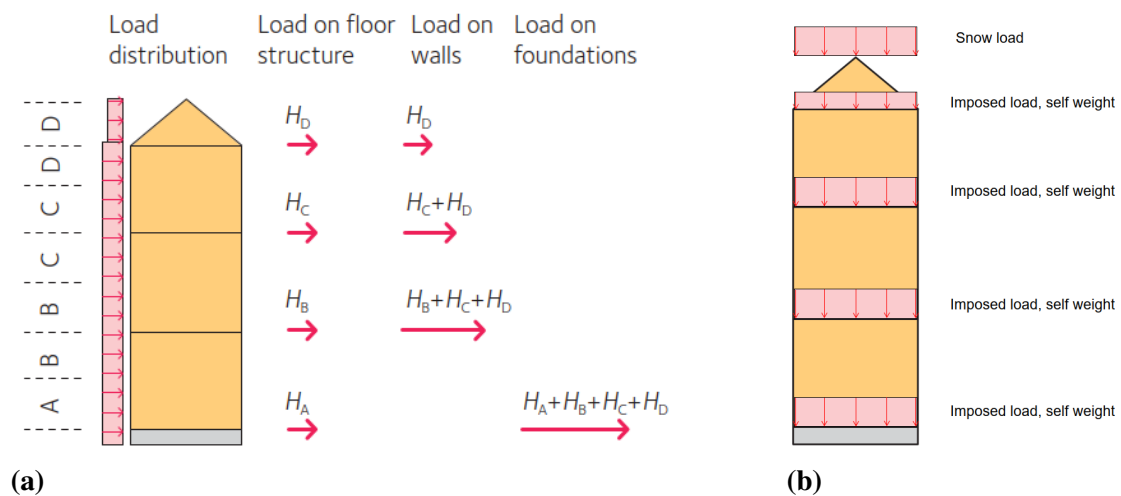


Figure 2.2: Loads acting on a CLT building. **(a)** Horizontal wind load (Swedish Wood, 2017). **(b)** Vertical loads such as imposed loads or self-weight (own illustration).

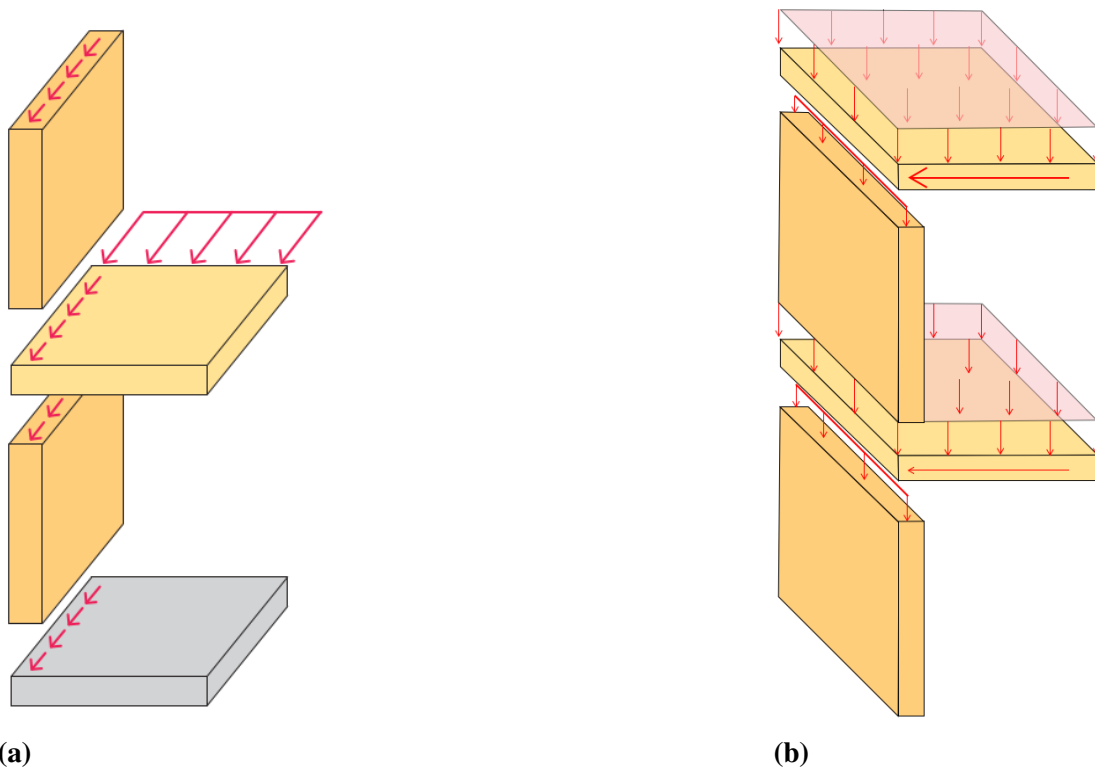


Figure 2.3: Load paths in a CLT building. (a) Horizontal wind load (Swedish Wood, 2017). (b) Vertical loads such as imposed loads or self-weight (own illustration).

To transfer forces between different CLT elements, appropriate connections must be used. To transfer the shear forces between CLT wall panels, the connection may consist of metal plates or screws only as can be seen in Figure 2.4 (Shahnewaz et al., 2018; Swedish Wood, 2017). The connection between CLT floor panels can be made similarly to wall panels. The floor-to-wall connection can consist of either screws, brackets or special types of connections, see Figures 2.10-2.12.

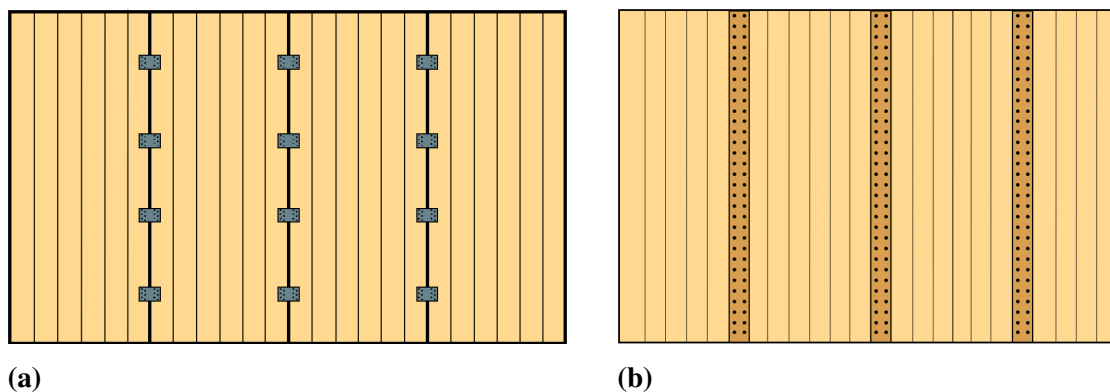


Figure 2.4: A CLT wall panel can be connected using either (a) metal plates or (b) screws (own illustration).

2.2.2 CLT Floor structures

CLT flooring is designed to withstand both horizontal and vertical loads (Swedish Wood, 2017). Usually, a CLT floor is made to carry the load in one direction, the longitudinal direction, which means that it is simply supported, according to Figure 2.5a. It can also be designed to carry the load in two directions, i.e., the longitudinal and transversal direction, as can be seen in Figure 2.5b. When vertically loaded, the CLT floor will be subjected to different kinds of stresses. It will experience bending stresses that are most severe in the outer layers of the panel and shear stresses that are the highest at the neutral axis (Brandner et al., 2016). Due to the cross-layering of boards to form the CLT panel, the transverse layers might govern for shear stresses lower than the maximum. Lastly, the compression perpendicular to the grain at the supports needs to be checked. Usually, it's the service state, with the deflection, vibration, and sound propagation, that governs the design of a CLT floor panel (Brandner et al., 2016; Ljunggren, 2023).

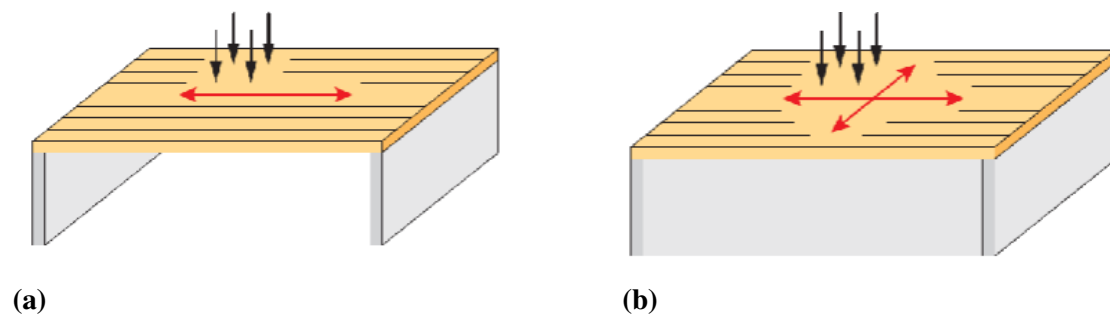


Figure 2.5: Vertical loads on a CLT floor panel carrying loads in (a) one direction and (b) two directions (Jockwer, 2024b).

A CLT floor can be made in different ways, such as plain CLT elements, built-up sections of CLT, and girders with or without flanges to provide increased capacity or to form longer spans or composite structures of CLT and concrete (Swedish Wood, 2017). Due to vibrations and sound propagation often being governing for the design of CLT floors, soundproofing measures often must be taken (Brandner et al., 2016; Ljunggren, 2023). Different measures to enhance the sound and vibration performance, as suggested by Ljunggren (2023), include a ceiling not connected to the load-bearing floor, implementing a so-called "floating floor" system, or having an elastic layer around the boundary to reduce transmission. The latter could be a vibration-dampening material, such as xylomer, in the connection of the CLT (Jarnerö et al., 2012).

2.2.3 CLT Wall structures

A CLT wall can serve as both an interior and exterior wall, often functioning as a structural and partitioning element, dividing between different rooms and protecting from external climate conditions (Swedish Wood, 2017). The walls are often complemented with additional insulation and cladding, as well as windows and doors. It can constitute

several units connected or one single unit, as can be seen in Figure 2.6.

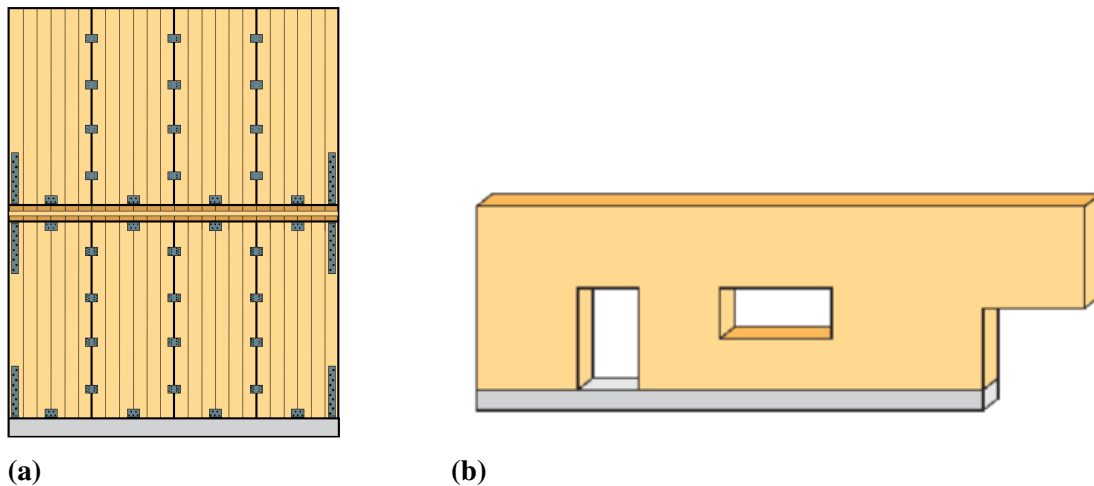


Figure 2.6: Different CLT wall configurations. (a) Single panels connected to each other (own illustration). (b) One large panel (Jockwer, 2024b).

A load-bearing wall is often a stabilizing unit that must withstand vertical loads from the floors above and horizontal loads from the wind (Swedish Wood, 2017). Due to the position of the above flooring, the vertical loads are often applied with an eccentricity that induces second-order effects. The vertical load is an axial compressive load that gives rise to a risk of buckling of the element. The horizontal load from the wind induces in-plane shear in the panel, which could lead to shear failure within the layer or rolling shear failure between the layers. A typical loading situation for a horizontally loaded CLT wall can be seen in Figure 2.7. As can be seen, the wind load gives rise to different force resultants, namely a shear force, and, due to the overturning moment, a compressive force and an uplifting force.

Horizontal wind load transferred via floor structure

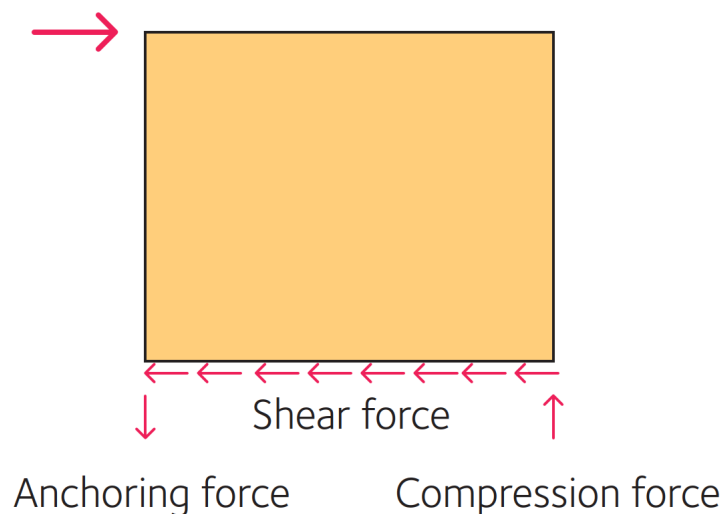


Figure 2.7: Horizontally loaded CLT wall (Swedish Wood, 2017).

2.2.4 Construction of CLT structures

As previously mentioned, CLT panels can take various shapes and sizes where the transportation capacity is the governing factor (Swedish Wood, 2017). Without additional permissions, in Sweden, it is possible to transport elements as large as 24 m x 2.6 m x 4.5 m. Normally, the CLT elements are delivered with moisture-proof packaging while waiting to be assembled. Due to timber structures being able to be built quickly, it is important to protect them from moisture during the construction phase so that no additional drying is needed, e.g., by using weather protection.

As CLT panels are prefabricated, the construction process becomes faster, more efficient, and less dependent on on-site labor, reducing overall construction time and costs (Bhandari et al., 2023). The panels are lifted into place using appropriate equipment, such as lifting eyes, straps, or steel chains (Swedish Wood, 2017). Once positioned, the elements are connected using suitable connectors, which can be either carpentry joints made entirely of timber or mechanical connections with metal fasteners designed for this purpose (Pozzi, 2019).

A CLT building can be constructed in different ways, which influence the structural system and its components, such as the connections (Mohammad et al., 2013). Two types of construction systems are *platform construction* and *balloon construction*, Figure 2.8. In Europe, platform construction is more common. In this method, floor panels are installed on top of the wall panels, forming a stable platform for the floor above. This method simplifies the building phases, uses straightforward connections, and clearly defines the load path. In balloon construction, the walls are continuous across the floors, with floors attached to the walls. This method uses more complex connections and complicates the construction phase. Due to the limited transportation capacities, balloon construction is used more in low-rise buildings, while platform construction is better for taller buildings.

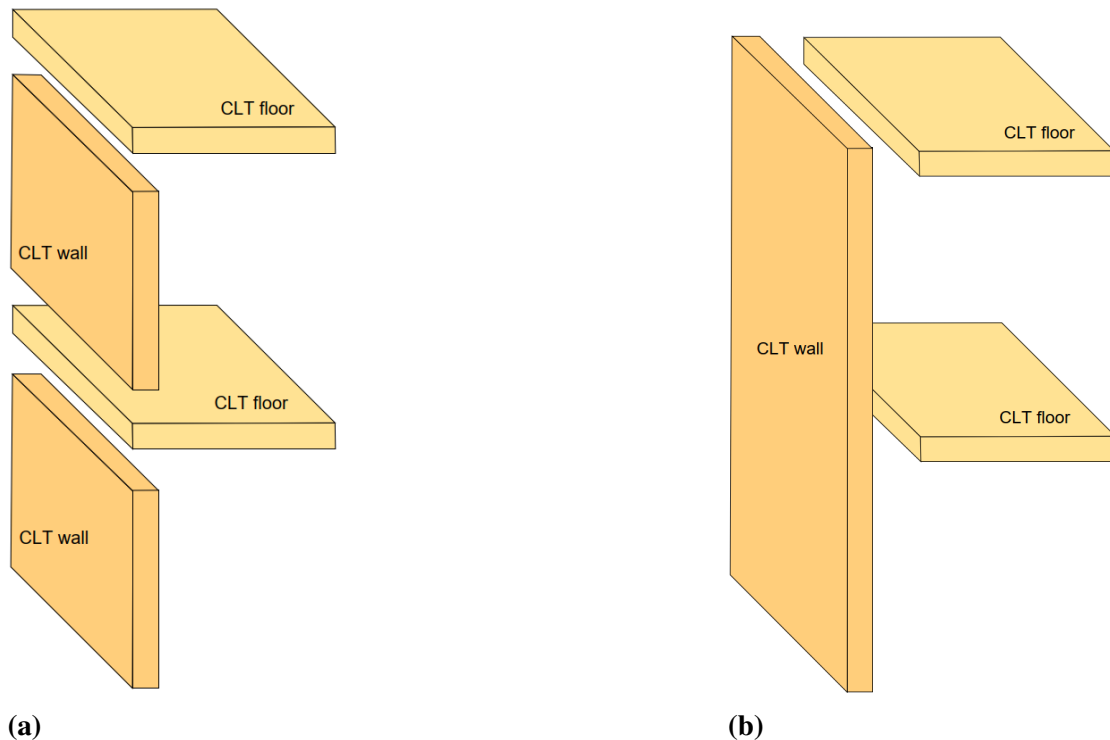


Figure 2.8: (a) Platform type and (b) balloon type of construction (own illustration).

2.3 Various types of timber connections and methods of dis-assembly

CLT is a versatile structural material that can withstand different types of loading configurations, such as vertical and horizontal loads (Swedish Wood, 2017). To transfer these forces between different elements, appropriate connection types must be used. This subchapter presents various types of metallic connectors used for attaching a CLT wall to a CLT floor, along with methods for disassembling these connections.

2.3.1 Screwed connections

The most basic connection type is by the use of construction screws (Swedish Wood, 2017). In this report, 'construction screws' refer to long, usually fully threaded screws used for timber-to-timber connections. See Figure 2.9 for an illustration of a screwed connection. Construction screws connect the floor to the underlying wall by being screwed vertically (Mohammad et al., 2013; Swedish Wood, 2017). The wall above is attached by screwing in at an angle, so-called skew screwing. When attaching the screws to the end of the CLT panel it is important not to screw them only into the end grain due to the parallel orientation of the fibers of the timber. To avoid this, skew screwing can be used to attach the floor to the bottom wall as well.

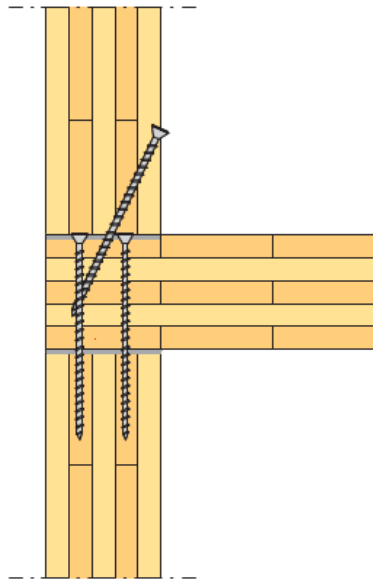


Figure 2.9: Screwed connection between a CLT wall and a CLT floor. (Swedish Wood, 2017).

2.3.2 Brackets

There are different kinds of metal brackets depending on what loading conditions the CLT panels are exposed to. For attaching a CLT wall to a CLT floor, commonly, an angle bracket is used for transferring the shear force generated by lateral loads (Mohammad et al., 2013). The uplift forces generated by lateral loads are handled by hold-down angle brackets, which are designed for tension forces (Liu & Lam, 2019). The brackets are attached by nails, screws, or bolts depending on the design of the connection (Mohammad et al., 2013; Ottenhaus et al., 2023). In this report, 'screws' refer to bracket screws used for attaching metal brackets or plates to wooden elements. In Figure 2.10, the lateral loading configuration and connectors can be seen. Brackets can also be used to transfer vertical forces when, for instance, a balloon-type of construction method is used (Mohammad et al., 2013). In Figure 2.11, a connection configuration that transfers vertical loads from a CLT floor to a CLT wall can be seen.

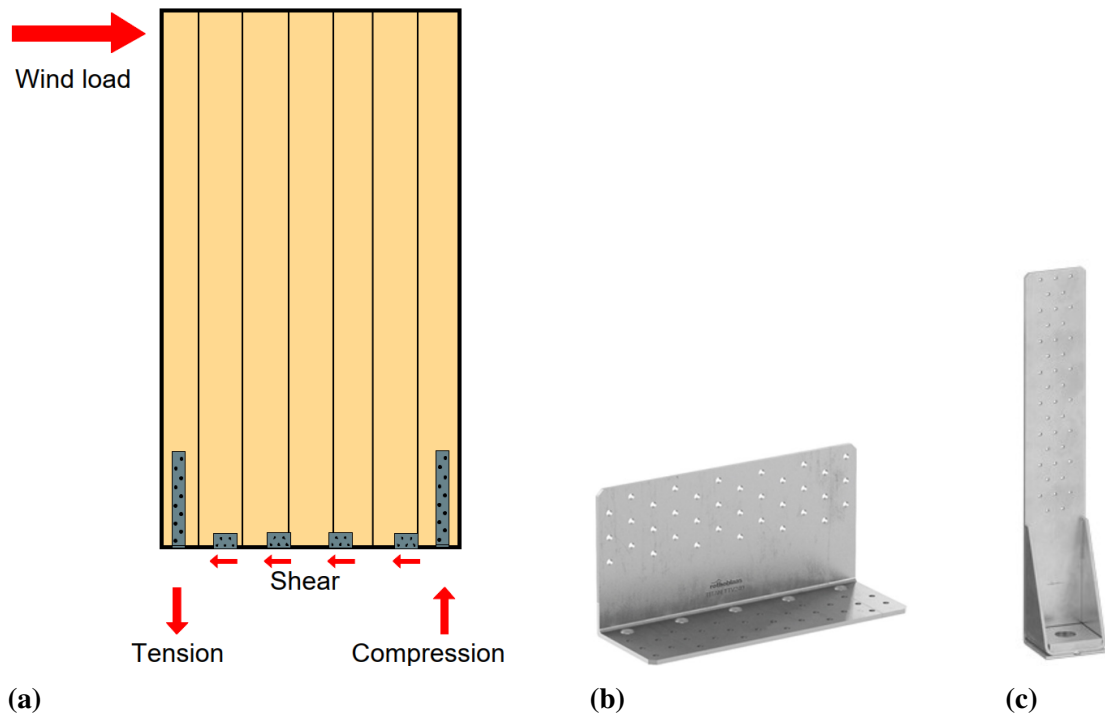


Figure 2.10: (a) Illustration of a laterally loaded CLT wall (own illustration). (b) Shear angle bracket, and (c) hold-down angle bracket (Rothoblaas, 2024).

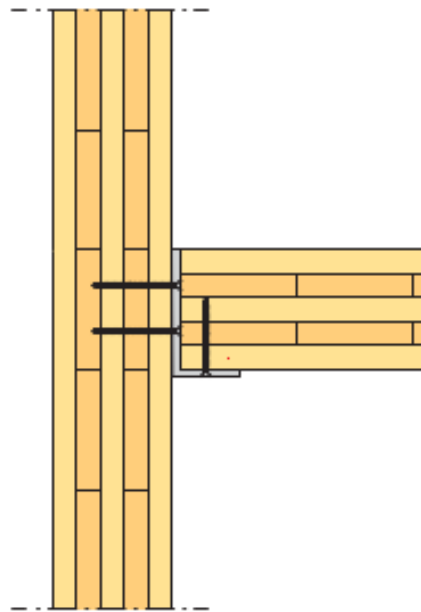


Figure 2.11: Connection between a CLT floor and wall designed to transfer vertical loads (Swedish Wood, 2017).

2.3.3 Other connection types

Other types of connections between a CLT floor and CLT wall could be made of slotted-in metal plates or glued-in threaded rods (Swedish Wood, 2017). The slotted-in metal plate connection are screwed to the CLT floor and then the CLT wall are placed such that

the plate are concealed within it, see Figure 2.12a. Threaded rod connections consist of rods glued into the CLT floor and wall, respectively, and joined using a threaded socket; see Figure 2.12b. Both these connection types require more complicated manufacturing processes, but the concealing of the connector elements improves the fire resistance significantly compared to a connection where the metal connectors are exposed (Ayansola et al., 2022; Mohammad et al., 2013).

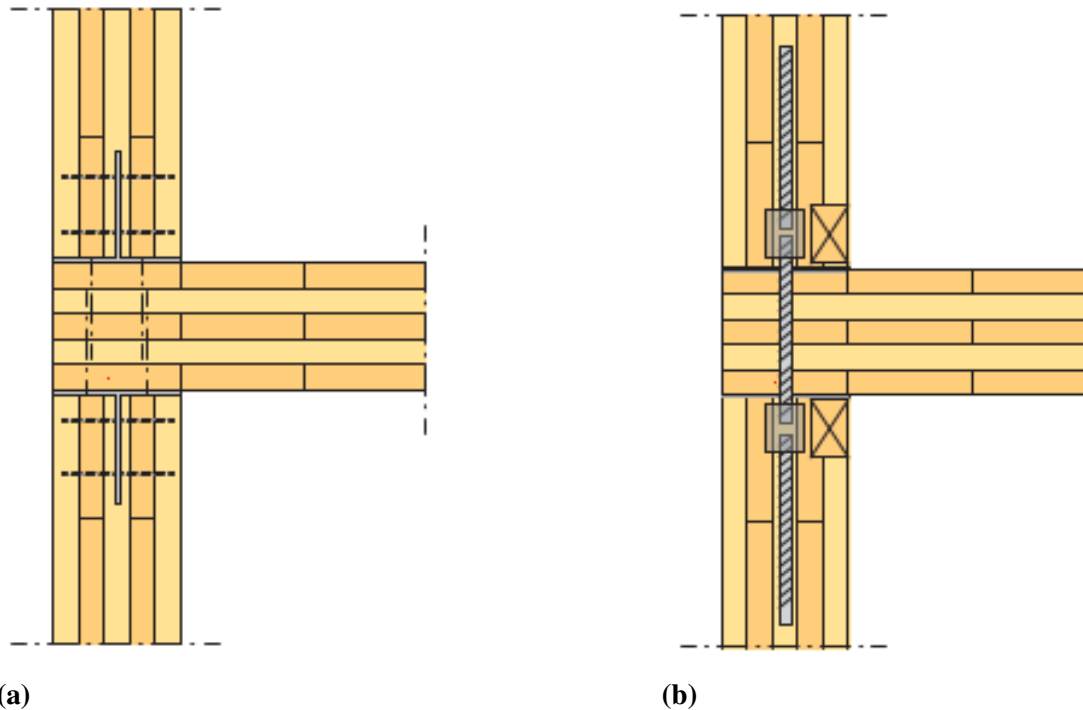


Figure 2.12: CLT wall to floor connection by using (a) a concealed metal plate, or (b) a glued-in threaded rod (Swedish Wood, 2017).

2.3.4 Disassembly of connections

Pozzi (2019) defines disassembly as "the separation of the elements and components of a building". According to Morgan et al. (2005), connection design is the single most important factor in determining whether a connection is detachable. A connection can be designed in various ways, which can be more or less easy to dismantle. Connections in which elements cover or conceal each other are harder to disassemble than those designed to be independent, highlighting the importance of accessibility. Lastly, connections that are glued or welded are, in principle, impossible to disassemble intact. In Table 2.1, different kinds of connection types are described, along with their respective pros and cons.

Table 2.1: Pros and cons of various connection types (Morgan et al., 2005).

Type	Advantage	Disadvantage
Screw	Effortless detachment	Usually single use of screw and screw hole
Bolt	Strong and reusable	Corrosion hinders removal
Nail	Quick attachment	Damages the element during detachment and is difficult to remove
Friction	No damage during deconstruction	Compared to other connections, it is both weaker and unexplored
Mortar	Strength can be varied	Not possible to reuse, and hard to separate
Resin	Strong and handles complex designs	Not possible to reuse
Adhesive	Strength can be varied	Not possible to reuse and hard to separate
Rivet	Quick attachment	Damages the element during detachment and is difficult to remove

As can be seen in Table 2.1, a screwed connection is generally easy to disassemble, but the screws and screw holes are usually not reused. This is due to the heat produced during the installation of the screw that softens the surrounding wood making it adhere to the screw when cooled, resulting in a torque above the maximum allowed when unscrewing (Ottenhaus et al., 2023). Furthermore, the reuse of the old screw holes reduces the strength of the connection which can be avoided by increasing the diameter of the screw or repositioning the connection location.

Bolted connections can be disassembled and reused as long as it hasn't been loaded above their yield capacity (Ottenhaus et al., 2023). Since the pre-drilled holes are slightly oversized, the disassembly process is often smooth. However, they can be hard to remove because they may become stuck due to possible corrosion (Morgan et al., 2005; Ottenhaus et al., 2023).

Nailed connections are difficult to disassemble because they lack a mechanism for controlled removal, unlike screws, which have threads that allow for precise detachment (Morgan et al., 2005; Ottenhaus et al., 2023). To disassemble a nailed connection, a crowbar is used to bend and pull the nails. This requires more force by the disassembler, resulting in a more labor-intensive process while also causing damage to the surrounding timber. Just as for a screwed connection, there will be holes remaining in the timber that has to be considered when reusing the element.

When disassembling a connection, the previous load history might have caused damage or deformation of the different connection elements (Ottenhaus et al., 2023). For instance, if the fasteners, such as screws, have experienced yielding and thus permanent plastic deformations the screws might be hard to disassemble. There could also be de-

formations in the steel bracket or in the timber itself, which will be further explained in Section 2.4.

2.3.5 Removal of structural elements

Another important aspect to consider when disassembling connections is that they need to be accessible. As can be noted in Figure 2.9 it is important to consider how the screws are attached to enable future disassembly. For instance, if the screw is covered by a timber element it can't be unscrewed without the covering element first being removed. This states the importance of what sequence needed for the disassembly process of a structure. For a connection using brackets, however, an intermediate element can be disassembled without removing the overlying elements, provided there is sufficient space for both the necessary equipment and the element itself within the room.

2.4 Failure modes

Connections in timber structures, such as those using CLT, can fail in several different ways depending on the type of loading, connection design, and material properties. Understanding these failure modes is essential to ensure a safe and reliable structural design. Typically, failure can occur either in the timber material itself, in the fasteners, or in the metal bracket (Swedish Wood, 2016). Additionally, the ductility of the connection, i.e., its ability to deform plastically before failure, plays a critical role in the performance of timber joints (Fernandez, 2023). The following sections describe the most common failure modes occurring in timber connections.

2.4.1 Failure in the timber or fastener

Connectors, or fasteners, carry load in mainly two directions, laterally and axially (Swedish Wood, 2019). While loaded laterally, the connectors will impose a pressure on the surrounding timber, which is called *embedding pressure*. When loaded axially, the connectors will primarily transfer forces along their length, leading to withdrawal forces (Sandhaas et al., 2018). Table 2.2 summarizes different failure modes for axially and laterally loaded fasteners.

Table 2.2: Summary of potential failure mechanisms in axially or laterally loaded single or group of fasteners (Sandhaas et al., 2018; Swedish Institute for Standards, 2005).

Loading	Failure mode	Failing material
Axial	Withdrawal	Timber
	Head pull-through	Timber / Steel
	Fastener tension	Steel
	Tension perpendicular to grain (splitting)	Timber
	Block shear and row shear	Timber
Lateral	Embedment	Timber
	Yield in bending	Steel
	Block shear, row shear, plug shear	Timber
	Tension perpendicular to grain (splitting)	Timber

Typically, a connection uses dowel-type fasteners, which include smooth dowels, bolts, nails, self-tapping screws, and staples (Wang et al., 2023). The main material parameters that are relevant when designing dowel-type connectors is: the *embedding strength* of the timber, f_h , the *yield moment* of the dowel, M_y , and the *anchorage capacity*, F_{ax} , which enables tensile action in the dowel (Swedish Wood, 2019).

Embedding strength governs how much stress the wood can take before experiencing large deformations in the connector's slot (Swedish Wood, 2019). This property depends on different parameters:

- The density of the timber, ρ_k , is of great importance, since this will determine how compact the timber is and, therefore, the "hardness" of the timber.
- The diameter of the connector, d , where a smaller connector will yield a larger embedding strength.
- The angle of the load compared to the fiber direction. Timber is stronger parallel to the grain and weaker perpendicular to the grain. Therefore, the load direction plays a large part in the embedding strength.
- Friction between the timber and the connector, with a rougher surface yielding a larger embedding strength.
- Moisture content in the timber. More moisture yields weaker material properties in wood, while less moisture yields stronger material properties.
- Reinforcing the timber in tension perpendicular to the grain will increase the embedding strength since failure is initiated due to cracks along the timber. These cracks usually appear due to the connector elongating the hole in the timber.
- If the connection is pre-drilled or not. When pre-drilled, the fibers will be cut off and stay straight, meaning that the load will be carried in compression parallel to the grain. However, when the connector is inserted without drilling, the fibers instead bend around the hole. This means that some of the load will be perpendicular to the grain, leading to a weaker performance.

The main parameters that decide the yield moment are the material property (usually steel) and the geometry of the connector (Swedish Wood, 2019). The yield moment of the connectors is based on empirical test data, and the given equations are used for three cases:

- $M_{y,RK} = \frac{f_u}{600} \cdot 180 \cdot d^{2.6}$ [Nmm] for round nails
- $M_{y,RK} = \frac{f_u}{600} \cdot 270 \cdot d^{2.6}$ [Nmm] for square and grooved nails
- $M_{y,RK} = 0.3 \cdot f_u \cdot d^{2.6}$ [Nmm] for all fasteners with $d > 8$ mm

The parameters affecting the anchorage capacity are the type and geometry of the fastener, the density and strength of the timber, the load direction relative to the grain, the number and arrangement of fasteners, and the embedment depth (Swedish Wood, 2019).

2.4.1.1 Lateral failure modes

The theory of laterally loaded timber connections was presented by K.W. Johansen in the 1940s and is the base theory used when designing according to Eurocode (Svensson & Munch-Andersen, 2018). The theory has been further developed throughout the years to include depth about the embedment strength of the timber and the yield moment of the fasteners. The theory states three different failure modes with the first mode appearing as failure in either timber parts (Swedish Wood, 2019). The embedment strength and the thickness of the timber parts will be governing, meaning that no yielding of the fastener will appear. This failure mode is represented by a(I), b(I), c(I), g(I), and h(I) in Figure 2.13. If the thickness of the timber is increased, failure modes two and three will take shape. The connector will yield, forming one plastic hinge for failure mode two and two plastic hinges for failure mode three. The second failure mode is represented by d(II), e(II), and j(II) in Figure 2.13, while failure mode three is represented by f(III) and k(III).

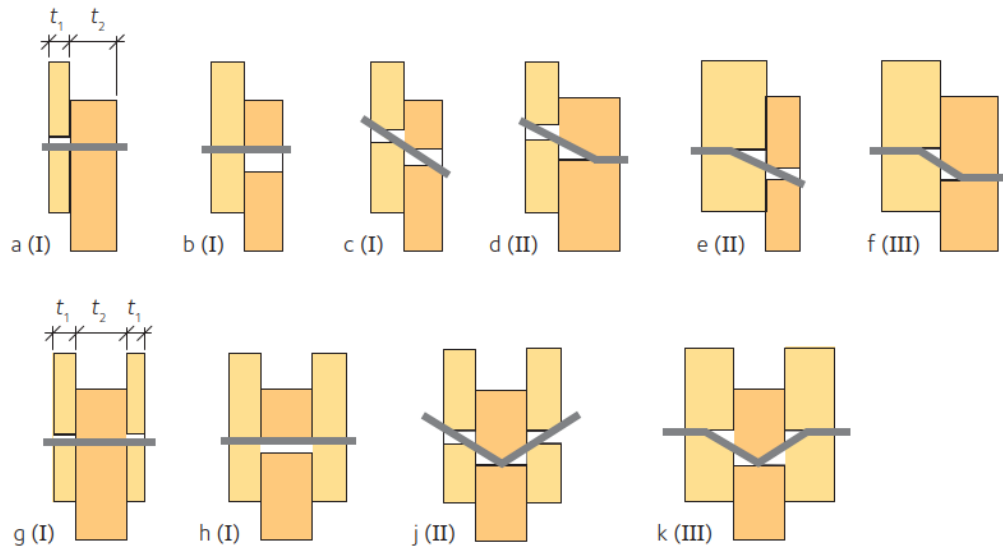


Figure 2.13: Failure modes for timber to timber connections (Swedish Wood, 2019).

For steel-to-timber connections, the dowel is considered in two extreme cases, one where it can be seen as pin-jointed and one where it can be seen as fixed (Blass, 2003). For a thin steel plate member ($t_{\text{steel}} \leq 0.5d$), the dowel will be able to move freely when it's inserted through the plate. This will result in a pin-joint, and no moment will be transferred, case a) in Figure 2.14. With a thicker steel member ($t_{\text{steel}} \geq d$), the dowel will instead be clamped, and the moment will be transferred. This will allow for a plastic hinge to form at the steel plate surface; see cases d) and e) in Figure 2.14. However, in the case of thin plates, there may still develop a plastic hinge in the timber if the dowel is slender enough, whereas for the thicker plate, there can develop two plastic hinges, see cases b) and e) respectively in Figure 2.14. For an intermediate thickness of the steel plate ($0.5d < t_{\text{steel}} < d$), interpolation between the thick and the thin steel plate failure modes can be made, resulting in a combined or mixed failure mode (Swedish Institute for Standards, 2004).

If the failure occurs in the timber only, with no deformation of the fasteners, disassembly is possible (Ottenhaus et al., 2023). However, if the failure happens in the fastener, depending on the extent of the deformation, the disassembly will be either very hard or impossible (Bompa et al., 2024; Derikvand & Fink, 2021; Ottenhaus et al., 2023).

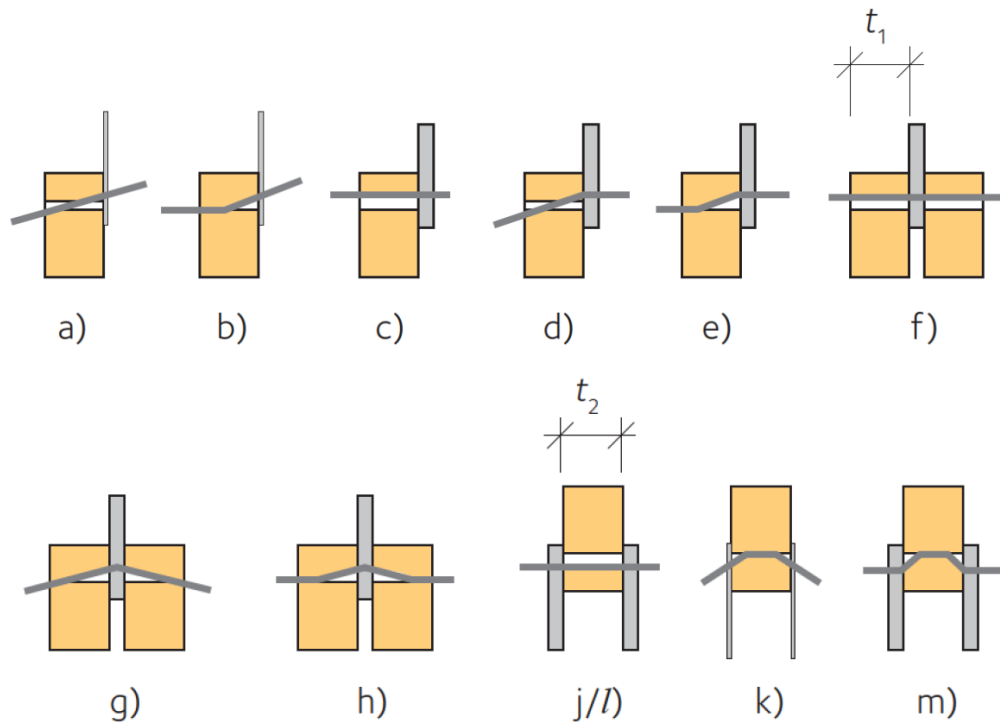


Figure 2.14: Failure modes for steel to timber connections(Swedish Wood, 2019).

Empirical studies have been performed to achieve equations for designing in timber (Swedish Wood, 2017). These differ depending on the type of timber product, as solid timber or glued laminated timber, compared to CLT. Due to the CLT having two main directions of the fibers (since the timber is cross-laminated) and because of gaps or grooves for stress relief, it is particularly important to consider the placement of the connections and their relation to the end wood (Sandhaas et al., 2018; Swedish Wood, 2017).

Other failure modes that could occur in laterally loaded connections are row shear failure, block shear failure, plug shear failure, and tension perpendicular to grain (splitting); see Figure 2.15 (Sandhaas et al., 2018; Swedish Wood, 2019). What these have in common is that they are all brittle failure modes. Different shear failures might occur when the connection is made of multiple rows of fasteners, and the risk increases when the fasteners are positioned close to each other (Swedish Wood, 2019).

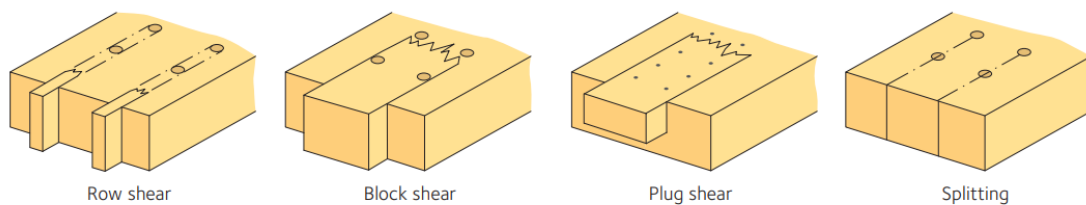


Figure 2.15: Brittle failure modes for doweled timber connection (Swedish Wood, 2019).

Block shear failure occurs when the timber around the fasteners shears off as a block (Swedish Wood, 2019). This mode is determined by either the tensile or shear capacity of the timber block and is affected by the net area at the end of the block and the net area of the sides of the block, respectively. Plug shear failure occurs, similarly to block shear failure, when the timber around the fasteners shears off as a plug. It is also determined by the tensile or shear capacity, and similarly, it is affected by different net areas. Row shear failure is when a row of fasteners causes the timber to shear off in a row. In general, row shear failure has a higher capacity than block shear failure due to the number of faces where the failure happens. Splitting failure happens when there are tensile stresses perpendicular to the grain, and it is, among other factors, affecting the effective number of fasteners, n_{ef} , used in calculations (Sandhaas et al., 2018; Swedish Wood, 2019). These failure modes all have in common that the timber has broken and the connection has detached from the main element, and therefore, disassembly does not need to be considered.

The fastener itself could also fail in either shear or bending. Shear failure occurs when the fastener is transversely loaded (Swedish Institute for Standards, 2005). Bending failure occurs due to eccentric loading, as in the case of using xylomer, which is illustrated in Figure 2.16. These failure modes depend on parameters such as the fastener geometry, material strength, and connection detailing.

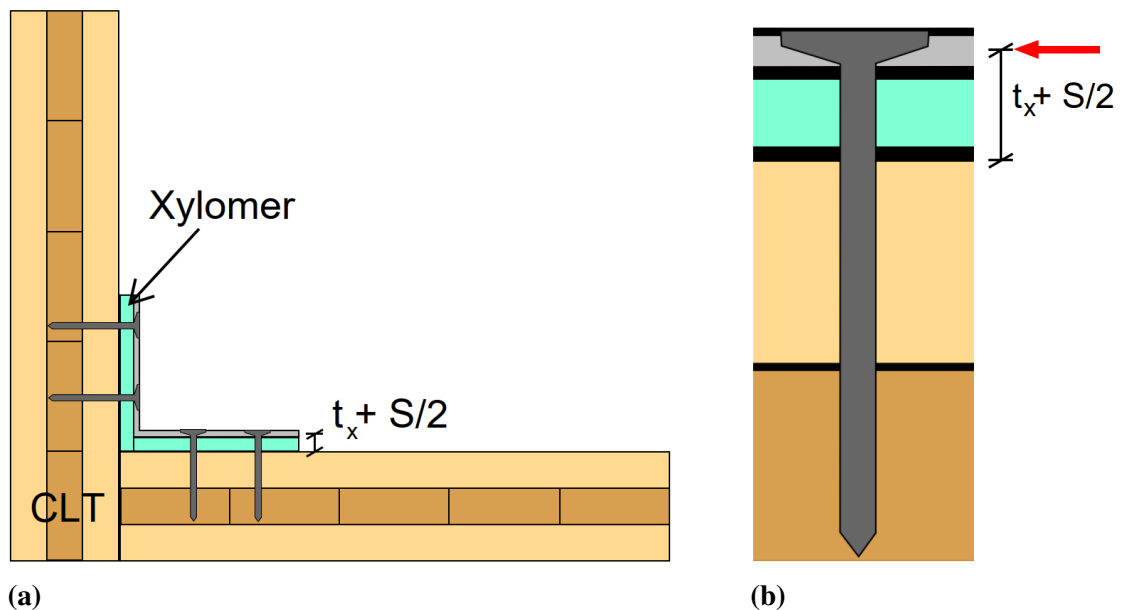


Figure 2.16: Illustration of eccentricity induced by xylomer with t_x being the xylomer thickness and S being the thickness of the bracket (own illustration). (a) CLT wall-to-floor connection with xylomer as a dampening material. (b) Close-up view of the fastener eccentricity with an indication of the applied load.

2.4.1.2 Axial failure modes

For axially loaded connections, fasteners that provide tensile anchorage are needed (Swedish Wood, 2019). These could be profiled nails, screws, or bolts with wash-

ers. The different failure modes that might occur in the timber part include withdrawal failure, head pull-through failure, splitting, block shear failure, and row shear failure. The fastener itself could fail in either buckling or tension due to its geometry and the capacity of the steel. See Figure 2.17 for illustrations of the different failure modes.

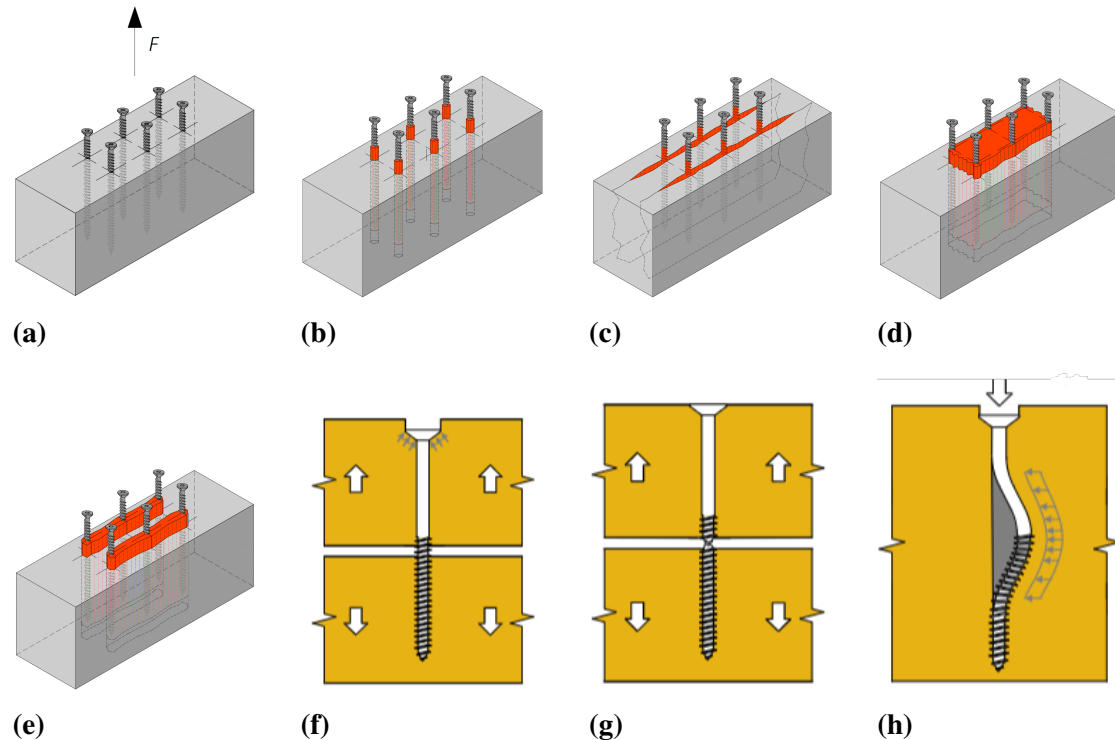


Figure 2.17: Failure modes of connections or fasteners subjected to axial loading. (a) Loading configuration, (b) withdrawal failure, (c) splitting failure, (d) block shear failure, and (e) row shear failure (Blaß et al., 2019). Adapted with permission. (f) Head pull-through failure, (g) Tensile failure, and (h) buckling failure (Jockwer, 2024a).

Withdrawal failure in a timber connection happens when the fasteners are pulled out from the timber due to axial tensile forces (Swedish Wood, 2019). It is affected by parameters such as the density of the timber, the type and geometry of the fastener, and the penetration depth of the fastener in the timber. Head pull-through failure occurs when the head of a fastener pulls through the timber (Jockwer, 2024a). This failure mode is influenced by the density of the timber, the size of the fastener head, and the characteristic pull-through strength of the fastener provided by the supplier (Isaksson et al., 2022; Simon Aicher & Weber, 2023).

The block shear failure mode is a combination of a shear and tensile failure in the timber, leading to a tear-out of a block of timber (Mahlknecht et al., 2016; Sandhaas et al., 2018). The row shear failure mode is a tear-out of the timber between the screws along the direction of the grain (Mahlknecht et al., 2016). Depending on the load direction, the failure occurs either as pure rolling shear or as a combination of rolling and transverse shear. Splitting is when the timber splits along the screw rows in the direction of the grain, leading to a withdrawal failure. These failure modes are influenced by

the penetration depth of the screws and their spacing, both along and across the grain (Mahlknecht et al., 2014, 2016).

The fastener itself could fail in tension, which is dependent on the geometry and strength of the steel (Isaksson et al., 2022). The tensile capacity of the fastener is provided by the manufacturer. The fastener could also fail in buckling when loaded under compression (Bejtka & Blaß, 2006). The capacity is determined by calculating the buckling load, considering an elastic bedding from the surrounding timber.

The failure modes that lead to the timber or fasteners being pulled out of the main element, such as withdrawal, splitting, block shear, and row shear failure, detach the connection from the element; therefore, disassembly does not need to be considered. Regarding the head pull-through failure, since the fastener isn't deformed, it can be disassembled (Ottenhaus et al., 2023). When the failure happens in the fastener, disassembly is possible as long as there hasn't been any significant plastic deformation.

2.4.1.3 Rope effect and group effect

When a connection that is laterally loaded in shear according to Johansen's theory in Section 2.4.1.1 has a failure mode that bends the fastener, see Figure 2.14, the connection will have a higher capacity than what Johansen's equations state (Swedish Wood, 2016). This happens after a fastener starts to yield and is due to the inclination of the fastener, resulting in tensile forces in the fastener (Debertolis et al., 2025). The capacity increase due to the rope effect, ΔF_{Rope} , depends on the smoothness of the fastener as well as its axial capacity. Screws provide the largest contribution, nails the lowest, and dowels do not contribute to the rope effect (Swedish Wood, 2016).

A connection usually consists of a group of fasteners. The load distribution varies between the fasteners due to local effects such as variation of strength in the timber, size of the fastener holes, misalignment, and uneven transfer of loads (Swedish Wood, 2016). The first and last fastener in a row of fasteners will be more loaded, resulting in them failing first. To account for this effect, an effective number of fasteners in a row parallel to the grain, n_{ef} , is used. This depends on the distance between the fasteners in the direction of the grain, the diameter of the fasteners, and the number of screws in the row.

2.4.2 Failure in the bracket

When designing steel-to-timber connections based on EN1995-1-1:2004, it's assumed that the failure will appear in the connector or the timber, hence the different failure modes in Figure 2.14 (Swedish Institute for Standards, 2004). However, the bracket in itself has to be able to handle the load it's exposed to. This appears as *bearing pressure* that develops when the bracket is loaded in shear from a dowel (Al-Emrani et al., 2011). There are different lateral failure modes that a steel plate can experience, with the first one being a net section failure. This will lead to the plate splitting on the sides of the hole. The second failure is a shear failure of the plate. This will result in the dowel

shearing off the plate towards the edge. The third failure is an elongation of the hole. See Figure 2.18 for an illustration of the different lateral failure modes. These failure modes are affected by the geometry of the bracket and the strength of the steel. In addition, the bracket itself must be checked for shear failure across its cross-section, especially near the dowel location where stress concentrations occur (Swedish Wood, 2017).

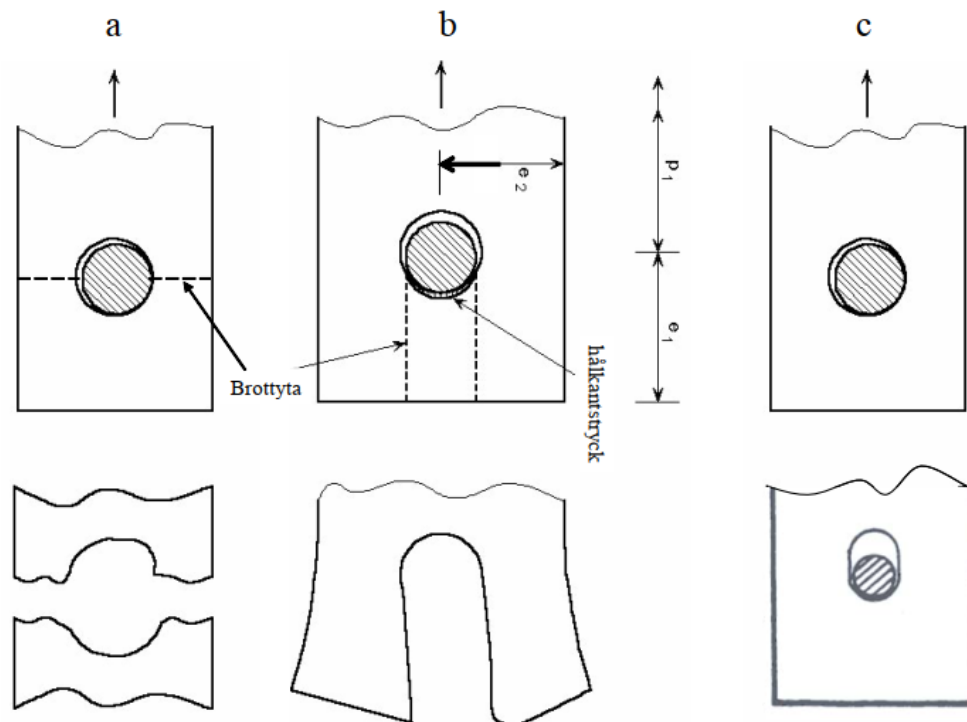


Figure 2.18: Failure modes of a laterally loaded steel bracket (Al-Emrani et al., 2011).

In a tensile axially loaded connection, the steel bracket might fail due to shear punching (Swedish Institute for Standards, 2005). It occurs when the concentrated force from a fastener causes shear failure around the hole in the bracket. It is influenced by the diameter of the fastener, the thickness of the bracket, and the strength of the steel.

A connection that has failed in the bracket, for instance, elongation of the fastener hole, is possible to disassemble (Ottenhaus et al., 2023). As long as the screw hasn't experienced severe deformation, the connection is fully disassemblable (Bompa et al., 2024; Derikvand & Fink, 2021).

2.4.3 Ductility

Ductility is defined as the "capacity of a material to deform permanently (e.g., stretch, bend, or spread) in response to stress" (Encyclopaedia Britannica, n.d.). Furthermore, ductility can be seen as "the ability of a structural member, a structural connection or a structural material to undergo large plastic deformations without significant loss of force capacity" (Fernandez, 2023). Ductility is an important factor of structural design

since its main purpose is to prevent sudden brittle failure and allow displacements that indicate overloading (Ottenhaus et al., 2021).

With timber being an anisotropic material, its behavior varies depending on the load direction (Swedish Wood, 2016). This leads to the constitutive behavior, which can be seen in Figure 2.19. Loading timber in tension deforms it elastically until the failure load, which will happen in a brittle manner. If the timber is loaded in compression, it exhibits the same elastic behavior initially but will eventually experience plastic behavior, leading to a more ductile failure. This applies to loading both parallel and perpendicular to the grain.

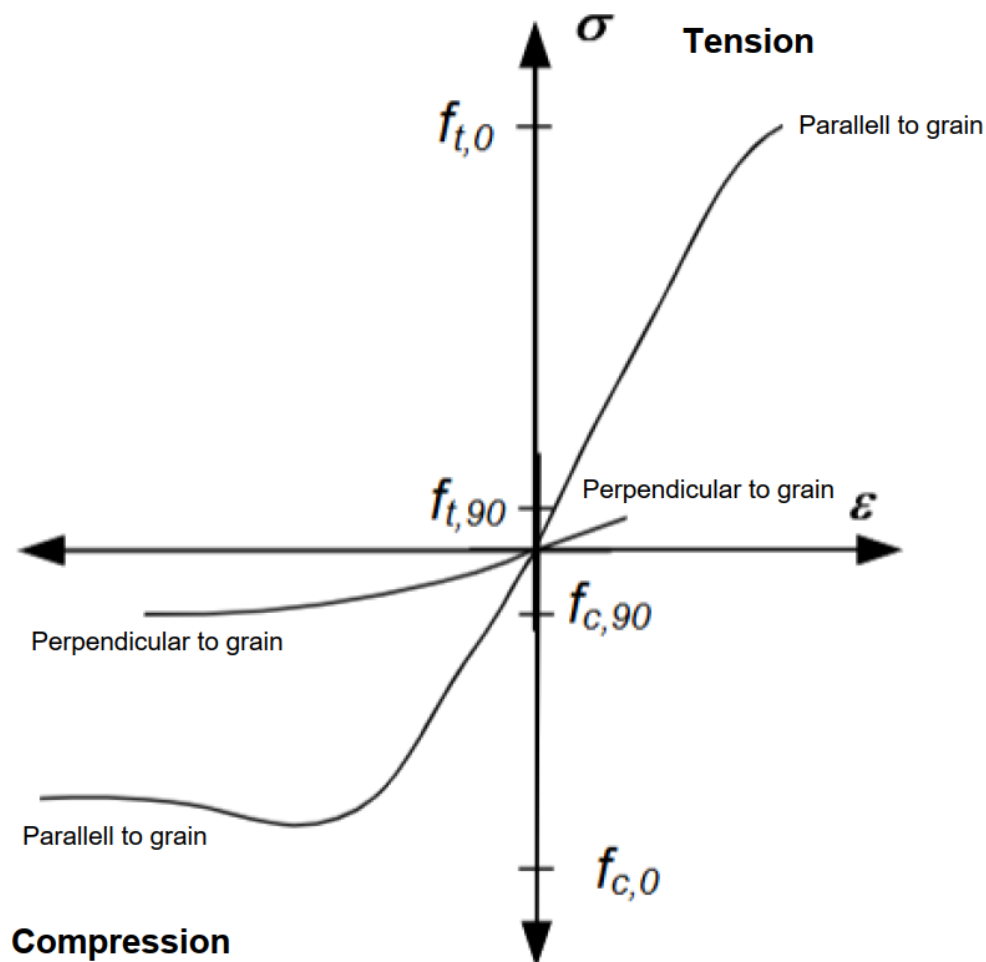


Figure 2.19: Stress-strain relationship for timber (Lundgren, 2021b).

In contrast to timber, steel is a homogeneous material that behaves the same in tension and compression (Hosamo & Sarwari, 2019). The stress-strain relationship of structural steel and high-strength steel, respectively, can be seen in Figure 2.20. For structural steel, such as in brackets, the material exhibits linear elastic behavior up to the yield stress, f_y . Beyond this point, plastic deformations occur, followed by strain hardening until reaching the ultimate strength, f_u . This ability to deform plastically, rather than failing suddenly, characterizes steel's ductile behavior (Ellobody, 2014). This pro-

vides visible warnings, such as large deformations, before failure. For high-strength steel, such as in screws, the capacity is increased but the ability to deform plastically is reduced, leading to more brittle failure (Al-Emrani et al., 2013).

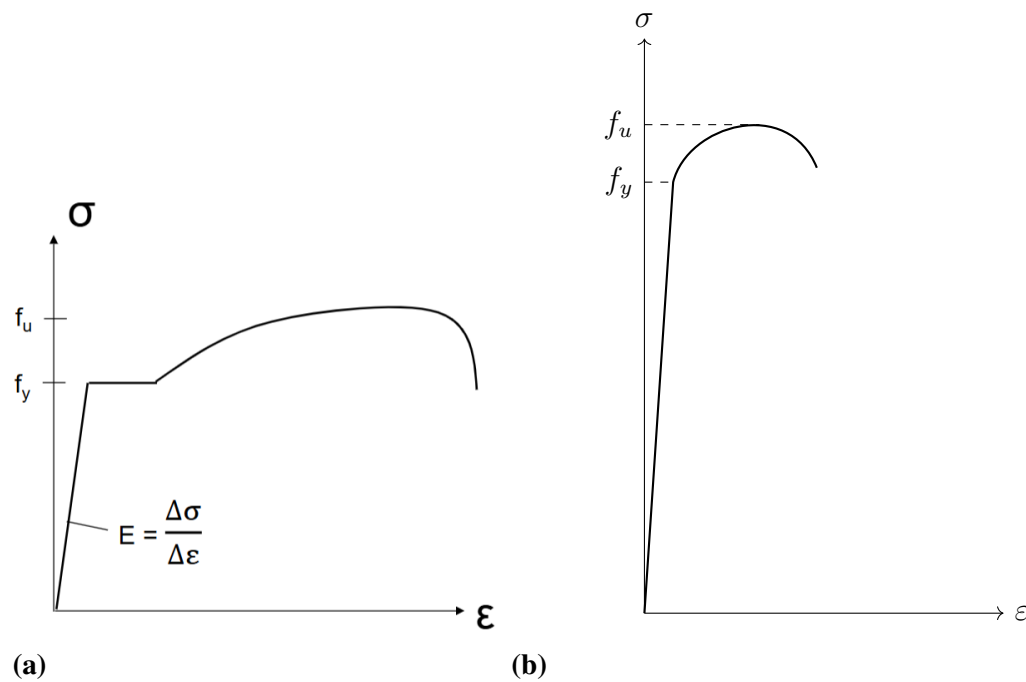


Figure 2.20: Stress-strain curves for (a) structural steel (Lundgren, 2021a) used in brackets, and (b) high-strength steel (Kontolati et al., 2017; own illustration) used in screws and bolts.

To ensure that a structure’s failure mode is ductile, an overstrength factor, γ_{Rd} , can be used (Aloisio & Fragiacomano, 2021). The overstrength factor ensures that a ductile failure mode is activated before a brittle failure mode by providing overstrength to the brittle failure mode. It is defined as the proportion of the characteristic load-bearing capacity of the non-ductile element, $R_{k,e}$, to that of the ductile element, $R_{k,d}$, see Equation 2.1. Based on previous experimental studies, the average overstrength factor for an angle bracket loaded in shear is $\gamma_{Rd} = 1.473$ (Gavric et al., 2015; O’Ceallaigh & Harte, 2019; Shahnewaz et al., 2017).

$$\gamma_{Rd} \cdot R_{k,d} = R_{k,e} \quad (2.1)$$

2.5 Genetic algorithm

A GA is an iterative search technique used to optimize models or problem solutions (Khanmohammadi et al., 2021). It is effective for solving complex problems involving many parameters. At each iteration, it randomly selects individuals and evaluates the fitness of each (Al-Emrani, 2022). The approach is inspired by the principle of natural selection, where the fittest individuals are selected to produce the next generation (Sircar et al., 2021).

The principles of a GA are to find the optimal, in terms of minimization or maximization, set of design parameters, $x = \{x_1, x_2, \dots, x_n\}$, that give rise to some properties, that is, the objective or fitness function, which is dependent on x (Al-Emrani, 2022). The design parameters are limited by an upper and lower bound that determines the design space, and the objective function could be limited by constraints. The algorithm stops when a stopping criterion is met, such as reaching a maximum number of generations, achieving a satisfactory fitness level, or no significant improvement in fitness over several generations.

The steps of a GA are outlined by Al-Emrani (2022) as follows:

1. Create a random initial population (generation). Evaluate the fitness of each individual in the population.
2. In several steps, use the best-fit individuals in the current generation to create the next population:
 - a. Scores each member of the current population by computing its fitness value.
 - b. Selects members, called parents, based on their expectation.
 - c. Some of the individuals in the current population that have lower fitness are chosen as elite. These elite individuals are passed to the next population.
 - d. Produces children from the parents. Children are produced either by making random changes to a single parent - mutation - or by combining the vector entries of a pair of parents - crossover.
 - e. Replaces the current population with the children to form the next generation.
3. The algorithm stops when one of the stopping criteria is met.

3 Methods

This chapter aims to present the different methods being used in this thesis, including descriptions of interviewed respondents, the case studied and setup of analytical approaches. Moreover, a literature review was performed beforehand to gain insights of the area of interest as well as to explain important theory for the thesis. The methods has been chosen to answer the aim and research questions in an effective way.

3.1 Interview study

To gain insights into reusability and its practical application, interviews were held with respondents from the construction industry. A total of three interviews were carried out, and to obtain the broadest understanding possible, representatives from the various parts of the industry were selected. This way, different perspectives were taken into account when forming a reusability criterion. The company's role and the respondent's role and experiences are stated in Table 3.1.

Table 3.1: Presentation of respondents.

Respondent	Role of company	Role of respondent
1	Design and manufacturing of brackets and fasteners	Currently working with sales and counseling, previously worked with CLT as a carpenter
2	Design and manufacturing of CLT elements	Currently working as a timber design specialist. The respondent deals daily with questions regarding design, calculation, and manufacturing.
3	Construction and assembly of CLT buildings	Founder of the company. Currently working with both project planning and assembly as a carpenter

The interviews were conducted in a semi-structured format, with the main questions determined beforehand but with room to adjust the questions as needed. Each interview lasted between 60 to 120 minutes and was held either in person or as a virtual meeting. The questions consisted of general ones regarding reusability as well as tailored ones specific to each respondent and their expertise. During the interview, the answers were noted in Swedish and translated to English using the AI-tool CoPilot. Moreover, the translation was double-checked for any mistakes. The answers were then analyzed using a simplified version of Braun and Clarke's (2006) method of thematic analysis to find key themes that were covered by multiple respondents.

3.1.1 Disassembly Effort Index

To get an idea of how assembly and disassembly are affected by fastener type, four different bracket connections were prepared for the interview with respondent 3. They all shared the same shear capacity, with the difference being the fastener type. The different connection configurations, including the type and geometry of the fasteners, are illustrated in Figure 3.1. Connection A used nails, Connection B used smaller screws, Connection C used larger screws, and Connection D used a nut-and-bolt configuration. The respondent was asked to rank these based on six different criteria with regard to assembly and disassembly: Time, Tools, Fixture, Instructions, Force, and Hazards. Their descriptions can be found in Table 3.2. This method is based on the multi-factor model created by Das et al. (2000), which results in a disassembly effort index (DEI).

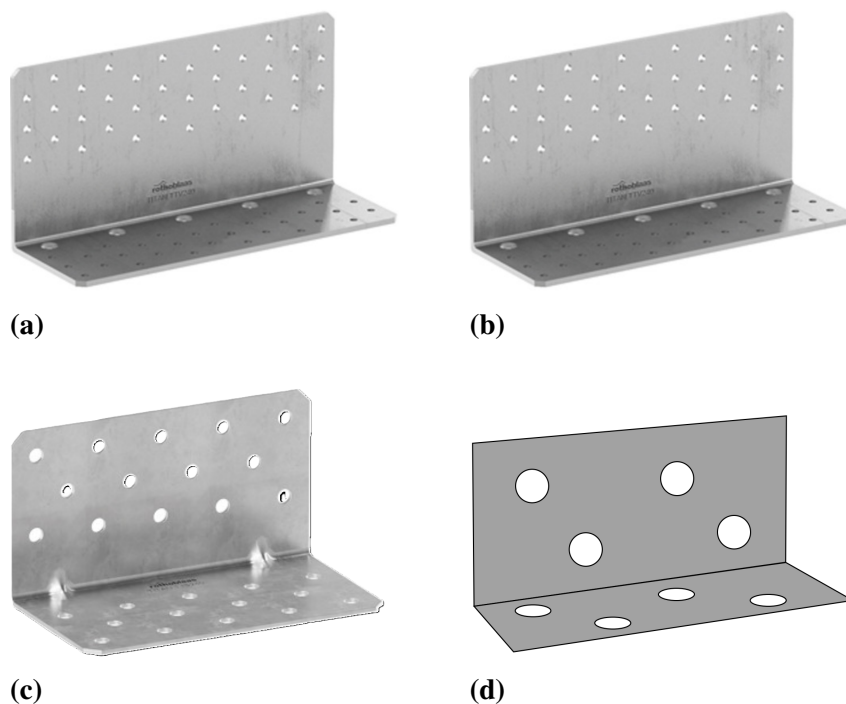


Figure 3.1: The connection types to be evaluated in the DEI are as follows: (a) nailed with 66 nails (4×60), (b) screwed with 66 screws (5×70), (c) screwed with 28 screws (8×80), and (d) bolted with 8 bolts (16×150) (Rothoblaas, 2024; own illustration).

Table 3.2: Description of the different DEI criterion for evaluation of different connection types.

Criterion	Description
Time	Total time to assemble/disassemble, including set-up time, handling time, and actual time to attach the bracket. Set-up time includes tooling and equipment preparation time.
Tools	All tools needed to perform the assembly/disassembly, including whether common or special tools are needed.
Fixture	Required fixtures needed (One-hand, two-hand, 2-person job, etc.)
Instructions	Methods to assemble/disassemble correctly without damage. More teaching is needed to perform the correct method.
Force	Force needed to perform the assembly/disassembly. Human force or machine force.
Hazards	Work environment (Vibrations, sound, other risks for injuries).

3.2 Case study

To design the connections in an appropriate way, a case study is conducted to determine the design loads and dimensions of the CLT elements. The case study is a project where PE Teknik & Arkitektur was responsible for designing the structural system. It is called Kv. Navaren and is a four-story apartment building with 2400 m² of liveable area (Månsson, 2025). The structural system, i.e., the walls, floors, and shafts, is made of CLT, Figure 3.2. Steel brackets and plates are used to connect the elements, with some fastened by screws and others by nails. Except for the shafts, the CLT walls are 100 mm thick, consisting of five layers of equal thickness. The floors also consist of five layers of lamellas with a total thickness varying from 160 mm to 200 mm. See Table 3.3 for a summary of the walls and floor sizes and the thickness of each layer.

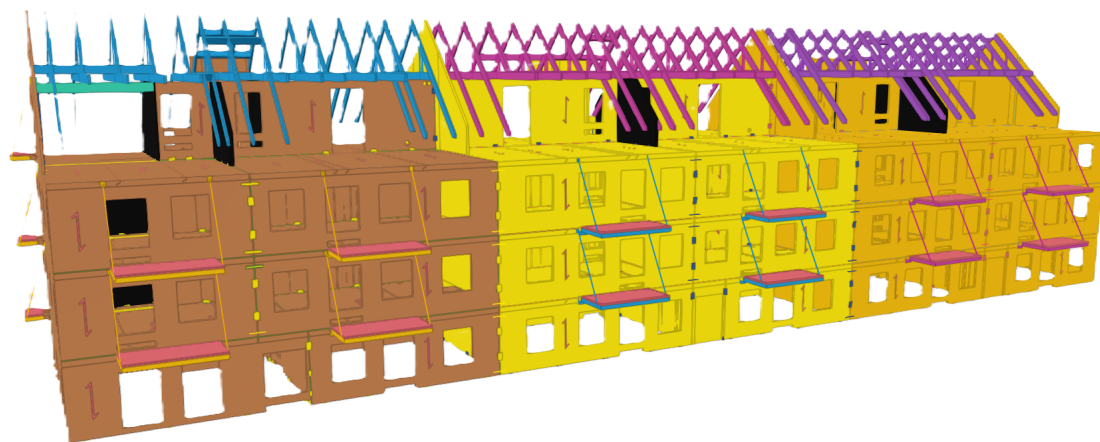


Figure 3.2: The structural system of Kv. Navaren.

Table 3.3: Built-up structure of the constituent CLT elements in Kv. Navaren. The table presents the layer thicknesses of CLT wall and floor elements in both the longitudinal (L) and transversal (T) directions, with dimensions given in [mm].

Element type	Thickness	L	T	L	T	L
Wall	100	20	20	20	20	20
	140	40	20	20	20	40
Floor	160	40	20	40	20	40
	180	40	30	40	30	40
	200	40	40	40	40	40

The building is situated in Mölndal, with terrain category III and a reference wind speed of 25 m/s for the horizontal loads. The vertical loads used for the design are a characteristic snow load of 1.5 kN/m² and dead loads and imposed loads as can be seen in Table 3.4.

Table 3.4: Dead loads and imposed loads in Kv. Navaren.

Load type	Category	Load (kN/m ²)
Dead Load	Roof structure	1.0
	Light partition walls	0.5
	Installation load (residential)	0.3
	Installation load (fan room)	0.5
	Terrace floor structure	1.0
Imposed Load	Floor structure (residential)	2.0
	Floor structure (basement)	3.0
	Roof surfaces	1.0
	Stairs	2.0
	Balconies	3.5
	Terraces	3.5

3.2.1 Governing loads

The characteristic wind load is $q_{ky} = 0.809$ kN/m² on the long side of the building and $q_{kx} = 0.679$ kN/m² on the short side (Appendix D). The wall on which the shear brackets will be studied, along with the tributary area for one floor, can be seen in Figure 3.3. Taking into account the floors above, the resulting characteristic shear force to that wall is 48.9 kN (Equation 3.1). Taking into account safety factors according to EN 1990 and EKS12, the design load is 73.35 kN, as can be seen in Equation 3.2 (Boverket, 2023; Swedish Institute for Standards, 2002).

$$F_{w,i} = q_{ky} \cdot 7265 \text{ mm} \cdot 2775 \text{ mm} = 16.3 \text{ kN}$$

$$F_w = 3 \text{ floors} \cdot F_{w,i} = 48.9 \text{ kN} \quad (3.1)$$

$$F_{w,d} = F_w \cdot 1.5 = 73.35 \text{ kN} \quad (3.2)$$

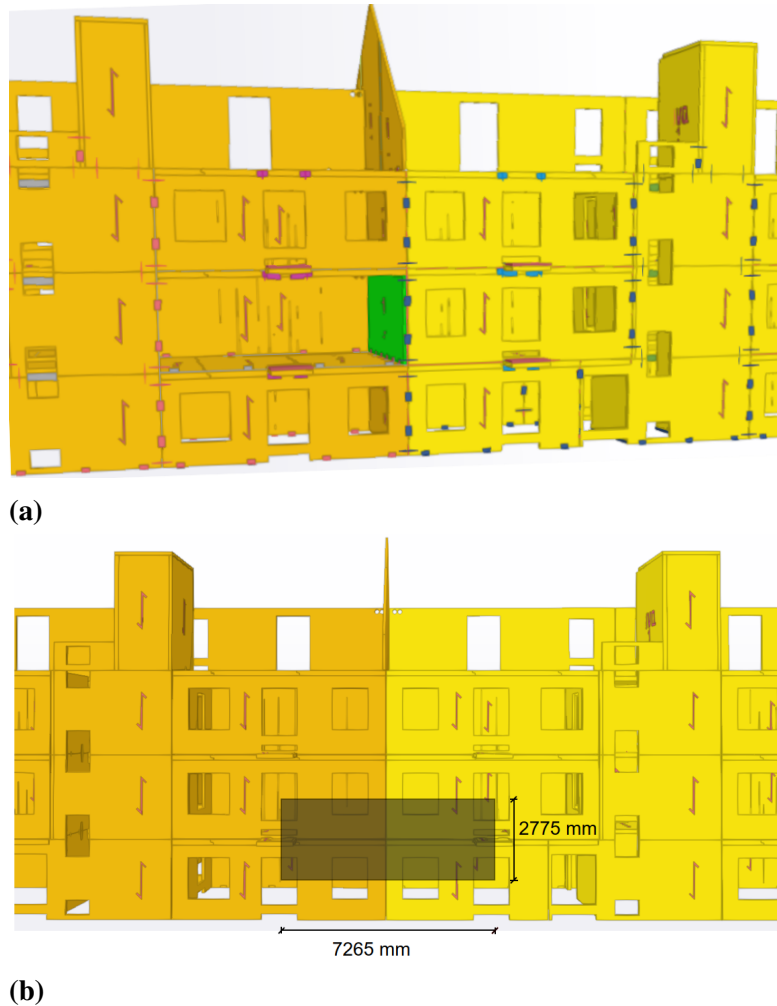


Figure 3.3: (a) The wall where the shear brackets will be investigated (marked green) and (b) its tributary area for the wind load.

3.3 Analytical investigation

To investigate the studied connections, hand calculations were performed using relevant standards and design guidelines for the design of buildings and other structures, which were supplemented by a parametric study and an optimization algorithm.

3.3.1 Design according to Eurocode and CLT handbook

For the design of a CLT connection, consideration was taken regarding the capacity of the timber, fastener, and steel bracket, respectively. The design considering the timber and fastener is mostly covered by the European standards, EN 1995-1-1:2004, (Swedish Institute for Standards, 2004), and due to CLT not being covered in this standard, the CLT handbook (Swedish Wood, 2017) is applied when needed. The design regarding the steel bracket and a failure mode of the fastener is covered by EN 1993-1-8:2005 (Swedish Institute for Standards, 2005). This design was made to be able to calculate the capacity of the studied connection and to find which failure mode was governing. To validate the calculations, a comparison of the product manufacturers' provided capaci-

ties in the technical data sheet for different connection configurations was performed.

3.3.2 Parametric study

To find how different connection configurations affect what failure mode is governing and to provide a basis for the optimization of the connection, a parametric study was performed. The parametric study was conducted using varying parameters, such as the geometry of the bracket, the fasteners, and the number of fasteners. Figures 3.4-3.5 show the screw data and the bracket geometry which is the input parameters to be varied in the parametric study. The capacities of the different failure modes for different fastener and bracket configurations were then recorded.

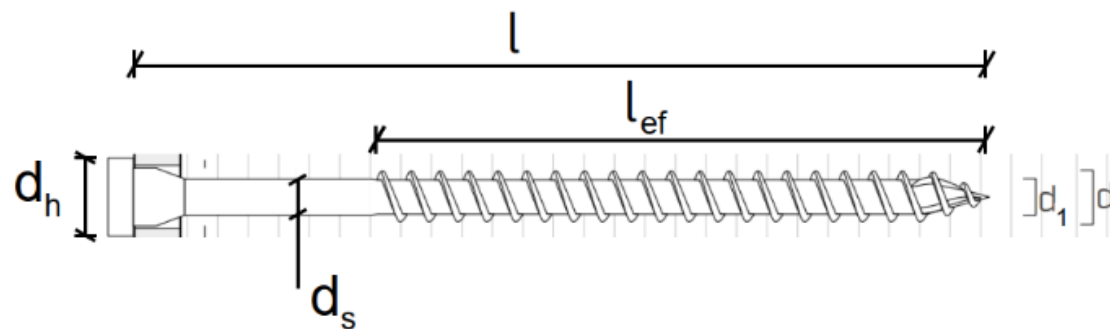


Figure 3.4: The screw input parameters varied in the parametric study include the outer thread diameter (d), inner thread diameter (d_1), head diameter (d_h), shank diameter (d_s), length (l), and the effective length (l_{ef}) (Rothoblaas, 2024).

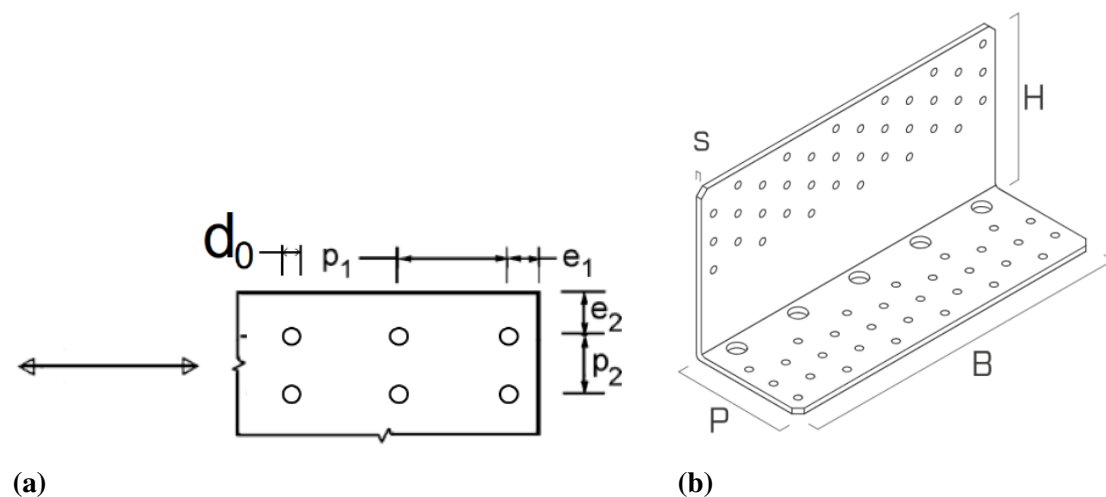


Figure 3.5: The bracket input parameters varied in the parametric study include: (a) hole diameter (d_0), spacing between holes (p_1 and p_2), edge distances (e_1 and e_2) (Swedish Institute for Standards, 2005); and (b) the overall geometry of the bracket, defined by S , H , B , and P (Rothoblaas, 2024).

3.3.2.1 Software tools

Different software was used to perform the parametric study in a structured and efficient way. In Mathcad, the design, according to Eurocode and the CLT handbook, was

performed (Appendix E). There, the calculation steps can be followed, and different connection configurations can be tested. To efficiently vary the input parameters and extract the output data in an organized manner, MATLAB was used (Appendix F). The MATLAB script is based on the Mathcad calculations and performs the same computations. However, it allows for faster and more efficient execution. The output data was then post-processed in MATLAB to generate diagrams that present the result.

3.3.2.2 Generation of input data

To establish a foundation for the study, screw input data was obtained from a recognized product manufacturer. When the required screw diameter and length did not meet the standardized configuration of the screws, interpolation and extrapolation was used to estimate the necessary dimensions and load capacities. The diameter (d) and length (l) were the main parameters varied in the parametric study. Based on these, the remaining input parameters, as shown in Figures 3.4-3.5, along with the withdrawal capacity of the screw, were determined. In Appendix G the screw input data can be found. Based on the hole diameter of the bracket (d_0) and the number of screws needed to carry the load obtained from the case study in Section 3.2, the bracket geometry was determined according to minimum distances defined in EN 1993-1-8:2005 (Swedish Institute for Standards, 2005).

3.3.3 Optimizing the connection

A GA was used to efficiently process the input parameters to optimize the connection configuration based on an optimization factor while maintaining the desirable failure mode (Appendix I). The GA was set up according to Figure 3.6 with the screw length and diameter varying as in Table 3.5. The bracket thickness varied as in equation 3.3.

$$t_{\text{bracket}} = \begin{bmatrix} 1.5 \\ 2 \\ 2.5 \\ 3 \\ 3.5 \\ 4 \\ 4.5 \\ 5 \\ 5.5 \\ 6 \end{bmatrix} \quad [mm] \quad (3.3)$$

The calculations performed are the same as in Appendix E but with geometries and failure mode as output for each iteration.

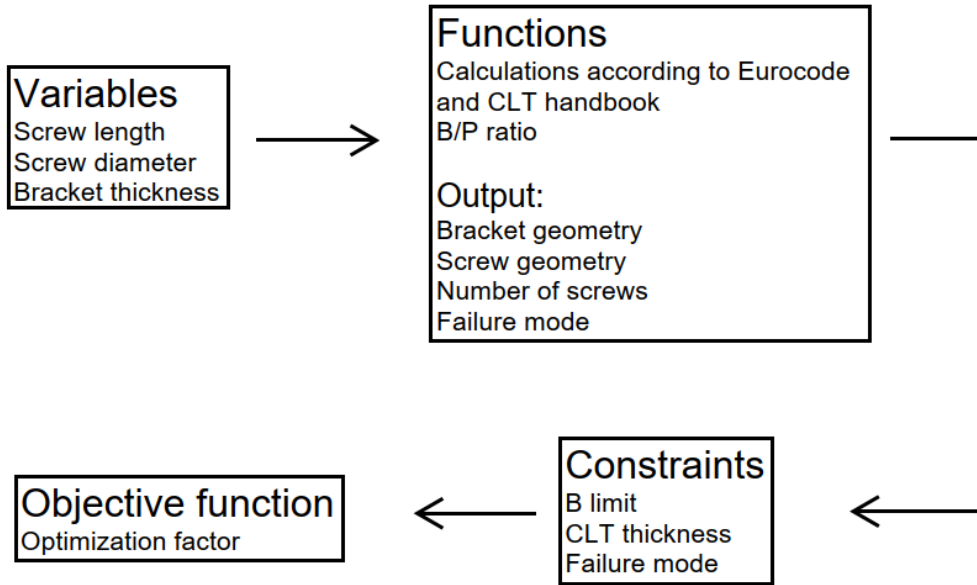


Figure 3.6: Scheme of how the GA optimization is set up.

The constraints are limited to a failure mode in the bracket, i.e., failure modes h and i in Table 4.2, as well as the geometric properties of the bracket and the screw. The geometric constraints are based on values from the case study in Section 3.2 and standard dimensions from commercial retailers. These include $B_{\text{limit}} = 250$ mm, a B/P_{ratio} of 240 mm/83 mm, and the condition $t_{\text{CLT}} - l \geq 20$ mm. While the B/P_{ratio} is not formally defined as a constraint, it governs the relationship between bracket width and depth in the functions part of the GA, thereby influencing the resulting bracket geometry. The specific geometries are illustrated in Figure 3.4 and Figure 3.5.

The objective function outputs the optimization factor, which evaluates the cost for each iteration and multiplies it by the total required number of fasteners in the connection, as in Equation 3.6, and the configuration with the lowest factor is selected as the optimal solution. The cost only includes the material costs, due to the labor costs being unavailable and hard to estimate. The material costs were obtained from commercial retailers. The screw costs can be seen in Table 3.5. The material costs for the bracket were obtained by taking the average price of the brackets in the case study, divided by their volume. The material costs for the bracket are 8.494×10^{-4} SEK/mm³, VAT excluded.

$$\textit{Optimization factor} = \textit{Price} \cdot N \quad (3.4)$$

$$\textit{Optimization factor} = (\textit{Price per screw} \cdot N) \cdot N \quad (3.5)$$

$$N = \textit{Number of screws} \quad (3.6)$$

The GA was run with different CLT wall-to-floor configurations based on the case study in Section 3.2. The different wall-to-floor configurations that were optimized can be seen in Table 3.6. For each of these configurations, an optimal connection configuration was obtained.

Table 3.5: Screw input for the GA. Price excluding VAT.

d [mm]	l [mm]	Material cost [SEK]
5	50	0.896
	60	0.960
	70	1.256
	80	1.496
6	80	1.728
	90	1.936
8	60	1.916
	80	2.508
	100	3.328
	120	3.664
	140	4.504
	160	4.780
10	80	3.176
	100	5.204
	120	5.764
	140	7.220
	160	9.560
	180	10.960
12	100	10.320
	120	13.320
	140	13.040
	160	14.560
	180	15.880
	200	17.640

Table 3.6: CLT wall-to-floor configurations for the GA.

Wall thickness [mm]	Floor thickness [mm]
100	160
	180
	200
140	160
	180
	200

4 Results

This chapter aims to present the results from the interviews, the parametric study, and the optimization.

4.1 Interviews

The interviews are presented mainly in two themes. The first one covers the general knowledge gained about reusability and the importance of standardization. The second theme focuses on the ease of disassembly, where the different fasteners are compared according to the provided method in Section 3.1.1. The complete answers to each question can be found in Appendix A, B, and C, respectively.

4.1.1 General and standardization

According to Respondent 2, no reusability of the CLT is being done today in Sweden, mainly because the CLT products are fairly new on the market and haven't reached their designated EoL. Some clients are starting to discuss reusability, but the respondent doesn't believe the logistics are available in the industry just yet. This is mostly due to the verification of the strength of the CLT being a key part of the certification process that confirms the element's usability. To assign a strength certificate for a reused panel, the data regarding its design loads needs to be available through a system like a digital twin. Furthermore, the respondent considered the handling and storage of reusable CLT panels as a problem, as it's not economically profitable enough.

Both respondent 1 and respondent 2 found that projects using CLT today vary substantially in their connections, with every project solving its connections in new, innovative ways. Moreover, Respondent 3 believes that special solutions in the connection should be avoided if disassembly is an important factor. They all see that standardization would be a good way to increase the efficiency in assembly while also allowing for easy disassembly.

4.1.2 Ease of disassembly

A reoccurring factor that all the respondents brought up was the usage of construction screws compared to brackets and screws. Respondent 1 mentions that connections using only construction screws needs to facilitate longer screws to achieve the same capacity as a bracket. With longer screws, problems emerge with the straightness of the screw due to it being more difficult to install accurately. Additionally, imperfections in the timber, such as knots, can further complicate the installation. Furthermore, the construction screws need more torque to be completely fastened which in turn creates a lot of heat, resulting in melting of the lignin in the timber. When this hardens around the screw, disassembly will be impossible because of the required torque needed to the screw. In most cases, this will result in the screw head tearing off and the rest of the

screw being permanently stuck. Respondent 3 also highlights this issue and further explains that even if the assembly is performed correctly, over time the building will experience settlements that can bend the construction screws. In the cases where assembly with construction screws has been performed incorrectly, respondent 3 says that in most cases they have to use a saw in between the CLT elements to cut through the screws to separate CLT elements, which is a comprehensive process.

Respondent 1 states that problems may sometimes occur with bracket connections if the mounting is performed incorrectly and assert that it's easy to over-tighten the screw. This will result in the weakening of the screw head and if there are significant moisture variations, there is also a risk of tearing off the screw head. Even though this can be a problem, Respondent 3 doesn't see any problem using brackets.

When comparing the different connections (A to D) presented in Figure 3.1, respondent 3 ranked them as in Table C.1, with the best one first and the worst one last.

Table 4.1: Grading, from best to worst, of the connections due to different criteria in DEI. Connection A used nails, Connection B used smaller screws, Connection C used larger screws, and Connection D used a nut-and-bolt configuration. Brackets indicate that the grade is equal for the connection.

Criterion	Grading (Connection A to D)
Time	Assembly: A, C, D, B
	Disassembly: C, B, D, A
Tools	Assembly: (BC), A, D
	Disassembly: (BC), D, A
Fixture	Assembly: (ABC), D
	Disassembly: (BC), A, D
Instructions	Assembly: C, B, A, D
	Disassembly: C, B, D, A
Force	Assembly: B, C, A, D
	Disassembly: B, C, D, A
Hazards	Assembly: C, B, A, D
	Disassembly: (BC), D, A

With regard to assembly time, nails are the fastest, mostly due to the process of insertion being instant when using a nail gun. This is followed by larger screws, nuts-and-bolts, and smaller screws. Even though a nut-and-bolt configuration uses fewer fasteners, the need for pre-drilling makes the process more time-consuming. When looking at disassembly time, respondent 3 claims that nails are the worst due to the process of

bending, twisting, and pulling of the nails. Instead, larger screws are to be preferred due to the larger heads being more resilient against torsional moment. With smaller screws, some screw heads might break which will slow down the process. Also, in a connection with smaller screws, there will be way more screws to disassemble. Respondent 3 has not worked with a nut-and-bolt configuration in a CLT connection but believes that the disassembly would be relatively fast.

For tools, the respondent ranked both screw configurations the same as they use the same machine for the assembly. They noted that a smaller screw will not need as big of a screwdriver as the larger screws, but this difference is minimal. For nails, a nail gun is needed, which is usually a bit heavier and more difficult to handle than a screwdriver. For the nut-and-bolt configuration, it's mentioned that the holes cannot be prefabricated in both connecting panels due to the tight tolerances. Instead, they can only be prefabricated in one element, while the other must be drilled on-site. Therefore, there is a need for both a drill and a screwdriver for fastening, making it the worst alternative. When disassembling, the respondent prefers the smaller screws for the same reason as for the assembly. Nails are, however, ranked the worst since they need crowbars, which are a destructive method of disassembly, or using a machine to cut the heads of the nails to release the bracket.

According to fixture, the respondent ranked nails, smaller screws and larger screws the same since they can be a one-man job, usually using two hands, but points out that a nut- and bolt connection can also be a one-man job depending on the design. Still, a connection with nuts and bolts may suffer from other problems, like access. For an angle bracket, the holes closest to the perpendicular element may be hard to access with larger machines like drills. When disassembling, small and large screws are still ranked the same as only one hand is needed while nails are seen as worse alternatives because of the use of two hands when using a crowbar or a machine to cut the nails. Depending on the design, nuts and bolts might need up to two people to disassemble and are, therefore, worse from a fixture point of view.

Regarding instructions, the nut-and-bolt setup will require more instructions to perform the assembly effectively and is, therefore, ranked as the worst. The nail gun can be a bit risky to use in the beginning, while also making it harder to correct mistakes. The screws are straightforward, with the larger ones being easier since there is less risk of over-tightening. To disassemble, the ranking is almost the same, with the nails being the worst. This is because cutting the nails with a machine will generate sparks, and handling this requires proper qualifications through a Hot Work certificate.

Concerning the force criteria, the smaller screws use less force than the larger ones. The nail gun is heavier than the screwdriver, and the drilling needed for the nuts and bolts configuration can be demanding, depending on the thickness of the CLT and the quality of the drill bit. The respondent notes that the drill bit will wear down quickly, making it harder to drill. Nails are the worst to dismantle since they demand a lot of manpower to

remove with a crowbar and/or cutting with a machine. Depending on the situation, nuts and bolts may be demanding too if corrosion has taken place.

Lastly, for the hazards criteria, the respondent placed the larger screws as the best ranking since it's the best from a health and safety point of view. The respondent says that the working position is uncomfortable, so the less time spent doing it is the better for the assembler. The respondent believes that connection D is the worst for assembly since there are a lot of steps in the process that are demanding on the worker. Nails are the worst for disassembly since the cutting will generate sparks and might cause fires. Connection D will make a lot more noise to remove, ranking it as the second worst. If using the same screwdriver, both connections B and C result in the same hazards connected to vibrations and noise generation. If a smaller screwdriver is used for connection B, it has a slight advantage, but it is almost negligible.

4.2 Parametric study

This section presents the results of the parametric study. Additional results not included here are provided in Appendix H. Each diagram indicates the expected failure mode, labeled $a-i$ or m . These failure modes are described in Table 4.2 and illustrated in Figure 4.1.

Table 4.2: Description of different failure modes for a CLT wall-to-floor connection. See Figure 4.1 for an illustration of the different failure modes. See Section 2.4 for a more detailed description.

Notation	Description
a	Rotation of fastener
b	Yielding of fastener, one plastic hinge (thinner plate)
c	Embedding failure
d	Yielding of fastener, one plastic hinge (thicker plate)
e	Yielding of fastener, two plastic hinges (thicker plate)
f	Shear failure of the fastener
g	Bending failure of the fastener
h	Failure in the bracket due to bearing pressure
i	Shear failure of the bracket
m	Mixed failure of a-e

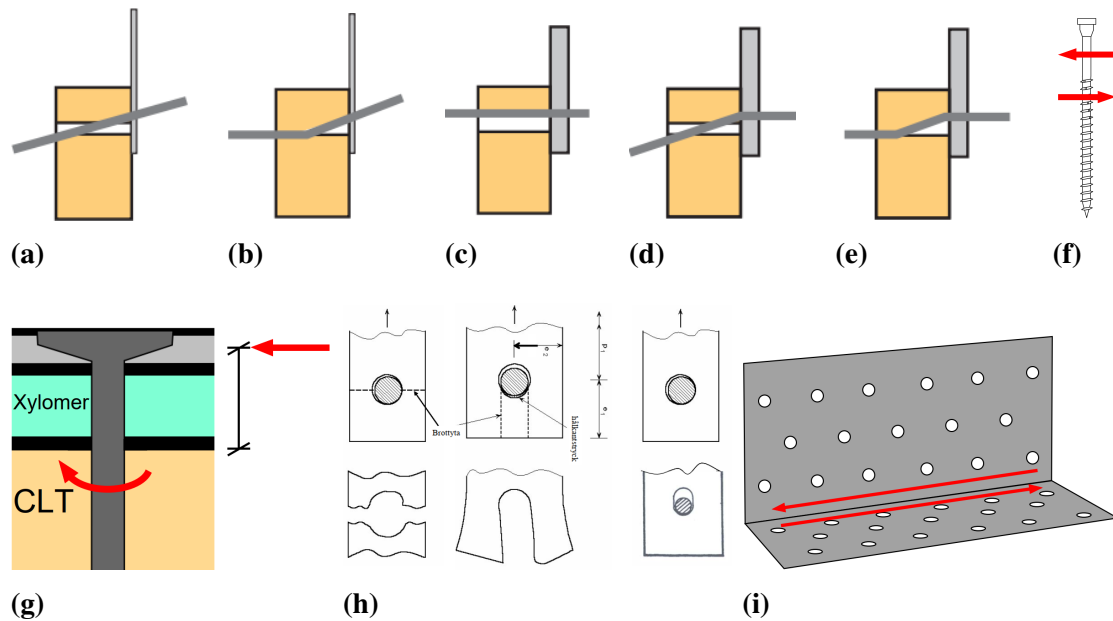


Figure 4.1: Illustration of the different failure modes for a CLT wall-to-floor connection as described in Table 4.2. (a–e) adapted from (Swedish Wood, 2019); (f) adapted from (Rothoblaas, 2024); (g, i) own illustrations; (h) adapted from (Al-Emrani et al., 2011).

For a CLT slab thickness of 100 mm, the capacity per fastener increases with an increasing diameter of the screw as shown by the solid lines in Figures 4.2-4.3. In the same figures it can be seen that for each screw diameter, increasing the bracket thickness leads to an approximately linear increase in capacity per fastener up to a bracket thickness of around 1.5–2 mm, depending on the screw length, with failure in the bracket (h) as the governing failure mode. Above this thickness, the capacity tends not to vary significantly, with failure in either the timber, fastener, or a mix of both as the governing failure mode. It is important to note that shear failure of the bracket (i) is not included in the calculation of the capacity per fastener, as it depends on the bracket geometry. For screw diameters of 8 mm and 10 mm, the capacity of the smaller diameter tends to approach and exceed the capacity of the larger diameter, as can be seen in Figure 4.4.

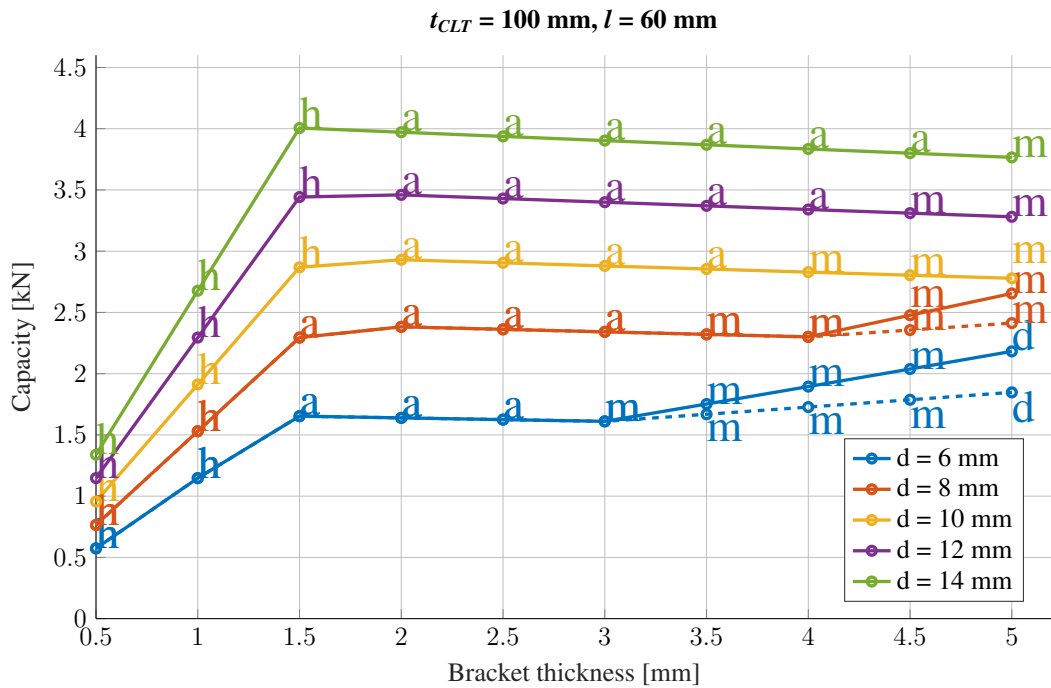


Figure 4.2: Load-carrying capacity per 60 mm long fastener for various fastener diameters and plate thicknesses, with a CLT thickness of 100 mm. Dashed lines are with the rope effect excluded. Governing failure modes are indicated according to Table 4.2.

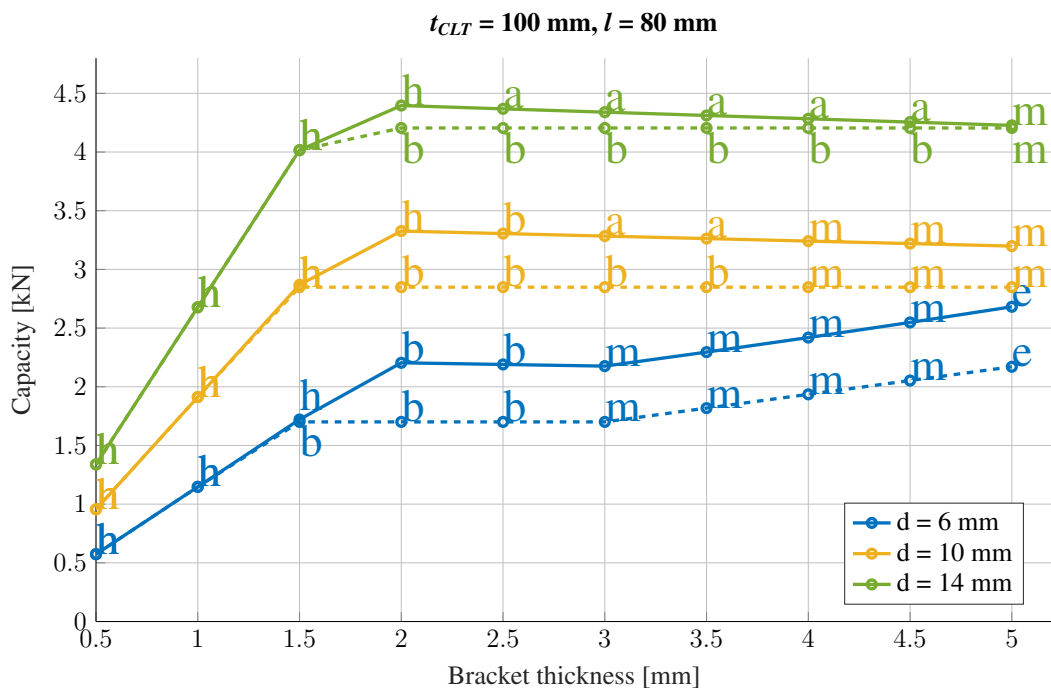


Figure 4.3: Load-carrying capacity per 80 mm long fastener for various fastener diameters and plate thicknesses, with a CLT thickness of 100 mm. Dashed lines are with the rope effect excluded. Governing failure modes are indicated according to Table 4.2.

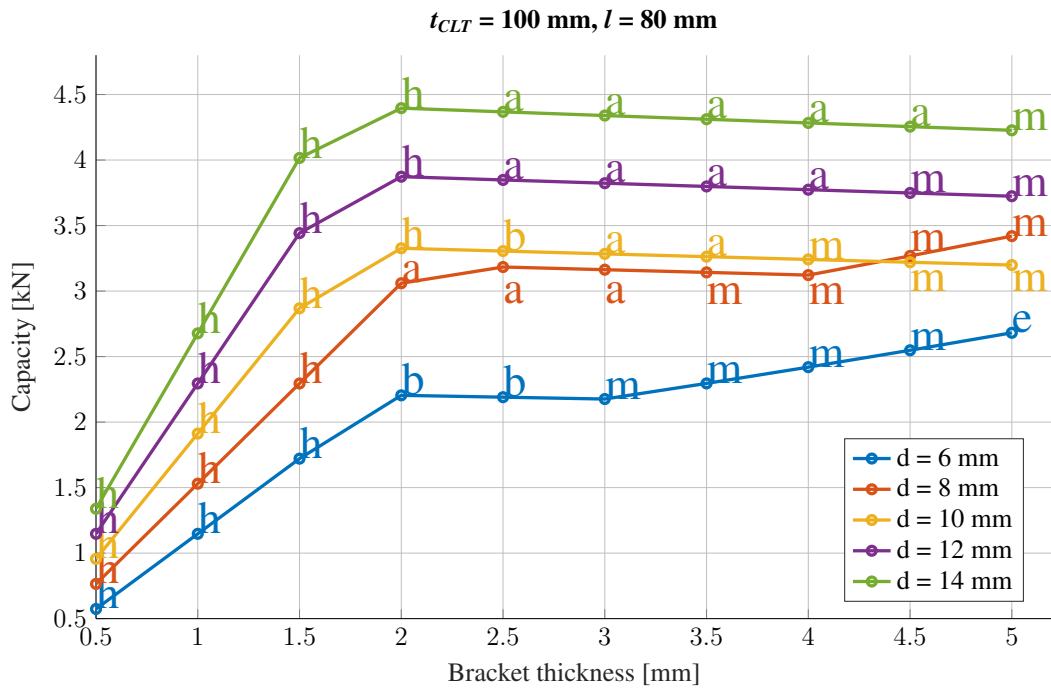


Figure 4.4: Load-carrying capacity per 80 mm long fastener for various fastener diameters and plate thicknesses, with a CLT thickness of 100 mm. Governing failure modes are indicated according to Table 4.2. This figure presents the same results as the solid lines in Figure 4.3, but includes additional fastener diameters for a more detailed view.

For the same CLT slab, i.e., with a thickness of 100 mm, the number of fasteners needed to achieve the capacity from the case study tends to decrease with an increasing diameter of the screw as can be seen in Figure 4.5. For each screw diameter, the number of fasteners needed decreases exponentially with an increasing bracket thickness up until around 2-2.5 mm with shear failure of the bracket (*i*) as the governing failure mode. Above this thickness, the capacity tends not to vary significantly, with failure in either the timber, fastener, or a mix of both as the governing failure mode.

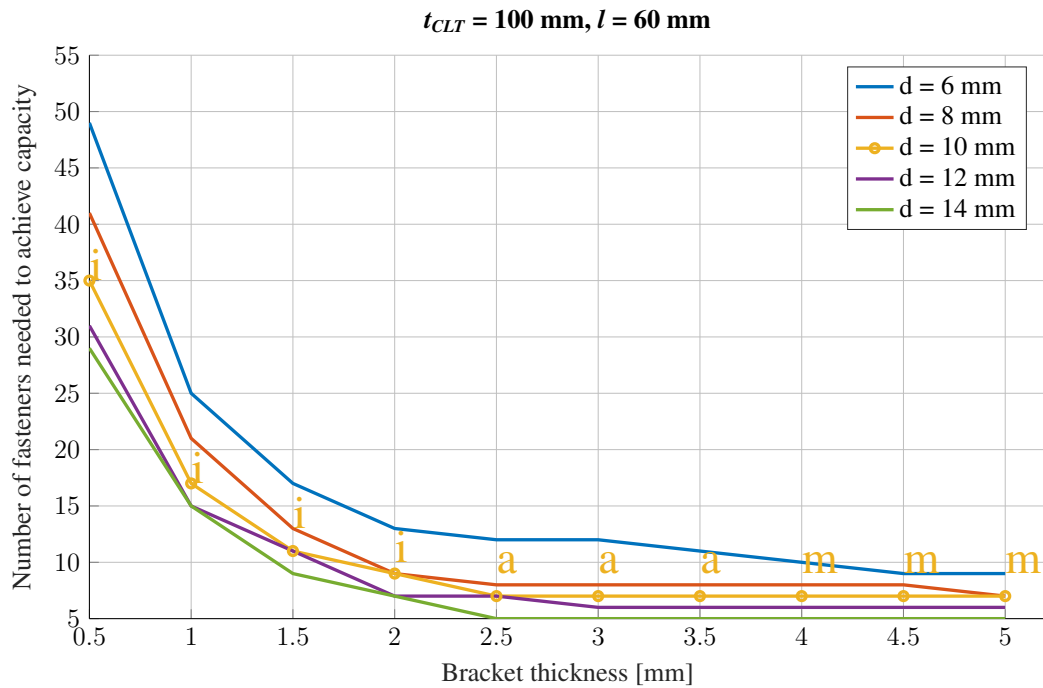


Figure 4.5: Required number of 60 mm long fasteners to carry the design load from the case study, shown for various fastener diameters and plate thicknesses, with a CLT thickness of 100 mm. For readability, governing failure modes are indicated only for the 10 mm diameter screw. See Table 4.2 for a description of the failure modes.

When looking at the results for the 100 mm thick CLT slab with the rope effect excluded, as the dashed lines in Figures 4.2-4.3, and Figure 4.6 the trend is similar to the case with the rope effect included, but the capacity per fastener is decreased, and the number of fasteners needed to achieve the capacity from the case study is increased. This entails, for each screw diameter, that the capacity per fastener increases up to a bracket thickness of around 1.5 mm, and the number of fasteners needed to achieve the capacity from the case study decreases up until around a bracket thickness of 2-2.5 mm. Above these thicknesses, there is no significant change in capacity or number of fasteners.

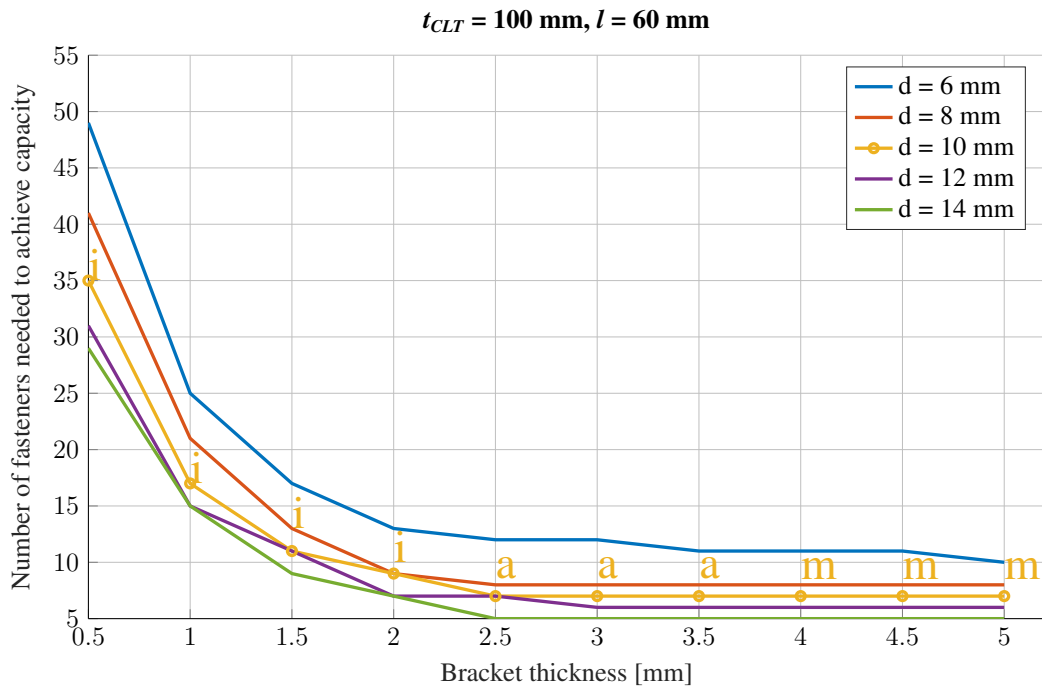


Figure 4.6: Required number of 60 mm long fasteners to carry the design load from the case study, with the rope effect excluded, shown for various fastener diameters and plate thicknesses, with a CLT thickness of 100 mm. For readability, governing failure modes are indicated only for the 10 mm diameter screw. See Table 4.2 for a description of the failure modes.

Figures 4.2–4.3 also illustrate the impact of the rope effect. Here, it can be noted that the rope effect becomes more significant for screws with a high length-to-diameter ratio. The rope effect indicates the point at which the fastener begins to yield, highlighting the importance of taking it into account when looking at the deformation of the connection. For instance, in Figure 4.3, at a bracket thickness of 2 mm, the 10 mm and 14 mm diameter screws show bracket failure (*h*) when the rope effect is included. However, when the rope effect is excluded, the failure shifts to the fastener (*b*), indicating that permanent plastic deformation has occurred.

For a CLT slab thickness of 200 mm, the result is similar to that of a 100 mm slab. As shown by the solid lines in Figures 4.7-4.9, what differs is that, for each screw diameter, the capacity per fastener now increases approximately linearly up to around 2.5-3 mm of plate thickness, depending on the screw length, with failure in the bracket (*h*) still governing. The same applies to the number of fasteners needed to achieve the capacity from the case study. As seen in Figure 4.10, the number of fasteners now decreases up to around 3.5-4 mm. Above these thicknesses, there is not much change in either the capacity or number of screws, and the governing failure modes is either in the timber, fastener, or a mix of both.

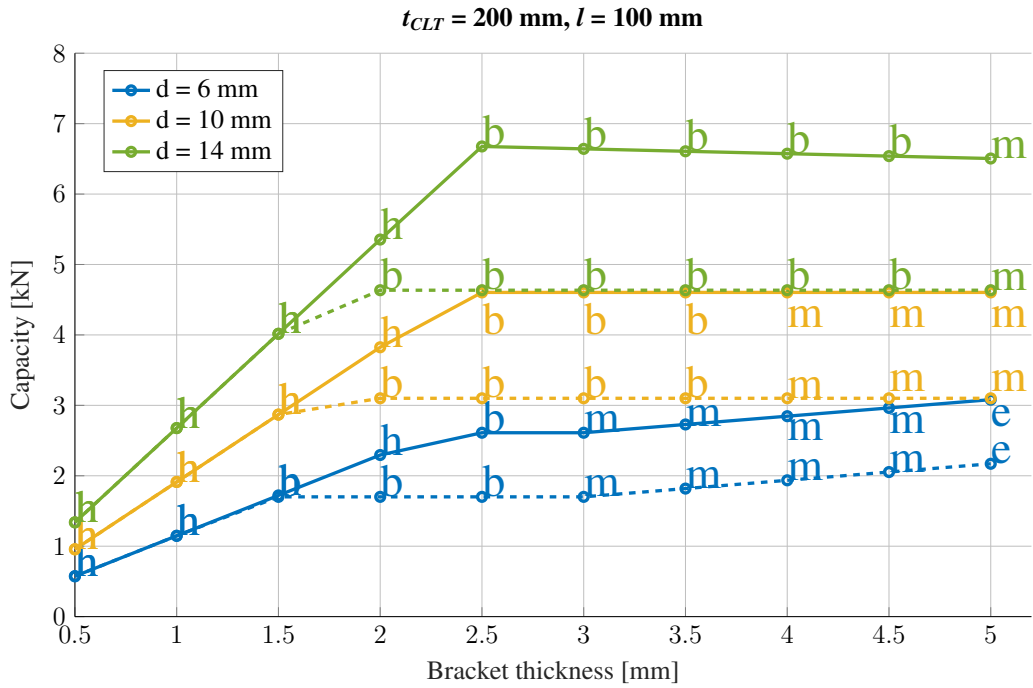


Figure 4.7: Load-carrying capacity per 100 mm long fastener for various fastener diameters and plate thicknesses, with a CLT thickness of 100 mm. Dashed lines are with the rope effect excluded. Governing failure modes are indicated according to Table 4.2.

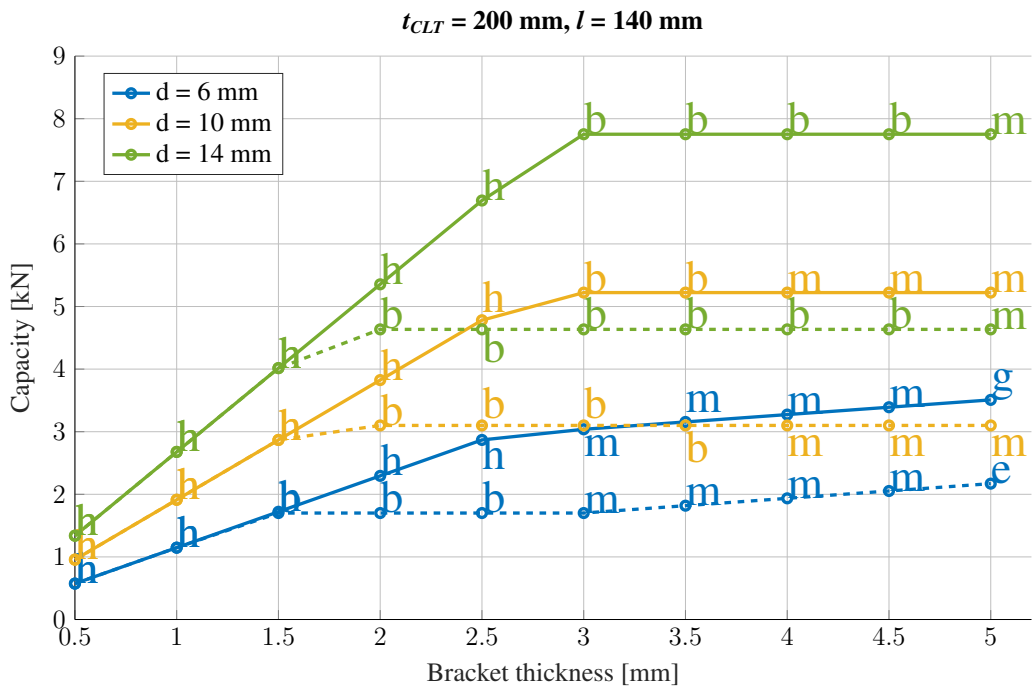


Figure 4.8: Load-carrying capacity per 140 mm long fastener for various fastener diameters and plate thicknesses, with a CLT thickness of 100 mm. Dashed lines are with the rope effect excluded. Governing failure modes are indicated according to Table 4.2.

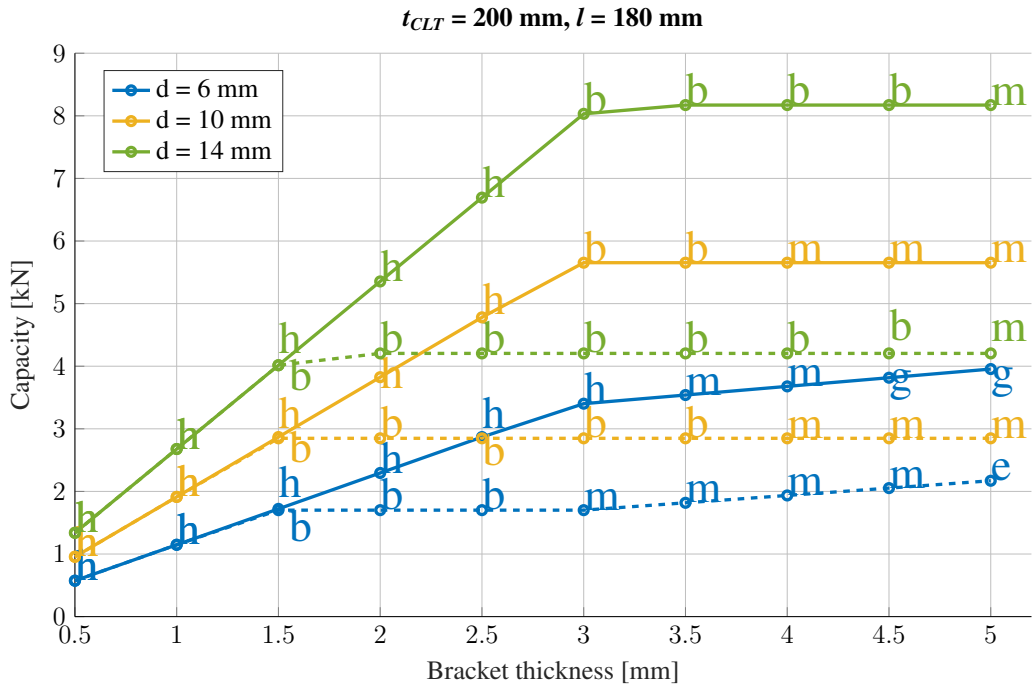


Figure 4.9: Load-carrying capacity per 180 mm long fastener for various fastener diameters and plate thicknesses, with a CLT thickness of 100 mm. Dashed lines are with the rope effect excluded. Governing failure modes are indicated according to Table 4.2.

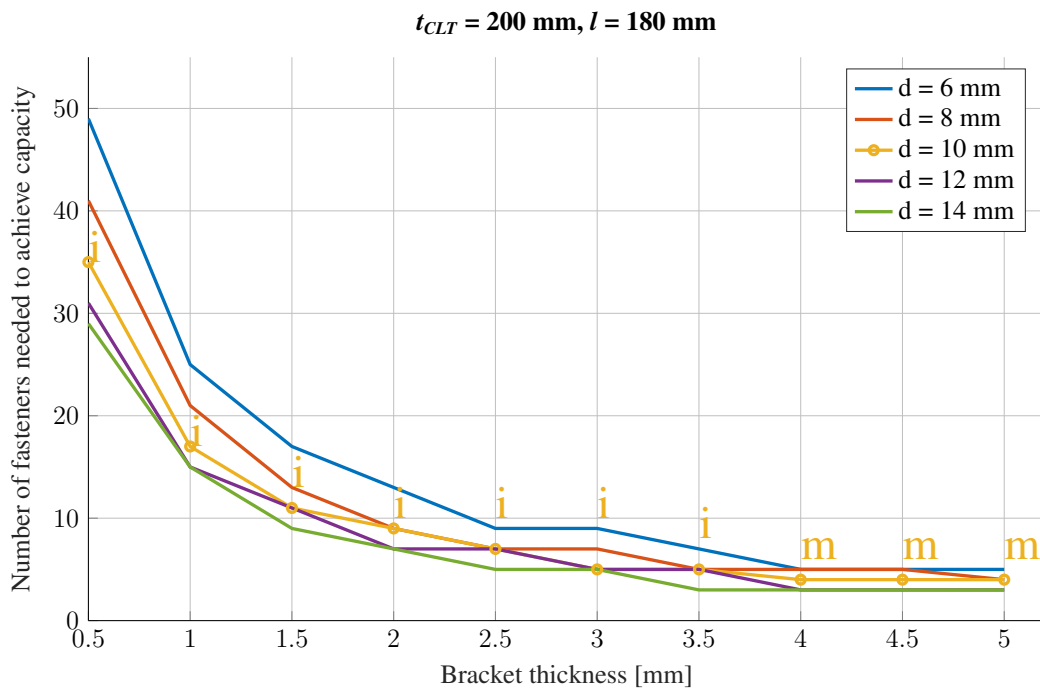


Figure 4.10: Required number of 180 mm long fasteners to carry the design load from the case study, shown for various fastener diameters and plate thicknesses, with a CLT thickness of 200 mm. For readability, governing failure modes are indicated only for the 10 mm diameter screw. See Table 4.2 for a description of the failure modes.

Regarding the impact of the rope effect, as can be seen in Figures 4.7-4.9, its depen-

dence on the length-to-diameter ratio can be seen as the difference between the capacities with and without rope effect, for each fastener length, increases with increasing diameter. It also shows that, for example, in Figure 4.7, a fastener with a bracket thickness of 2 mm may exhibit a situation where a failure mode including the rope effect governs in the bracket (*h*), while the capacity without the rope effect governs failure in the fastener (*b*).

In Figures 4.11-4.13, the capacities per fastener are compared for different CLT thicknesses and screw configurations, considering the effects of both the rope effect and the vibration-dampening material, xylomer. It can be observed that for smaller screws, i.e., screw lengths and diameters below 100 mm and 10 mm respectively, the xylomer has a significant impact on the capacity when the plate thickness exceeds 1.5 mm. For larger screws the xylomer has no impact for plate thicknesses up to 3 mm, above that the xylomer reduces the capacity slightly. Considering the effect of the rope effect, it can be seen that there is no significant impact of the xylomer on smaller screws. However, for larger screws the capacity of the screw is reduced when the rope effect is excluded.

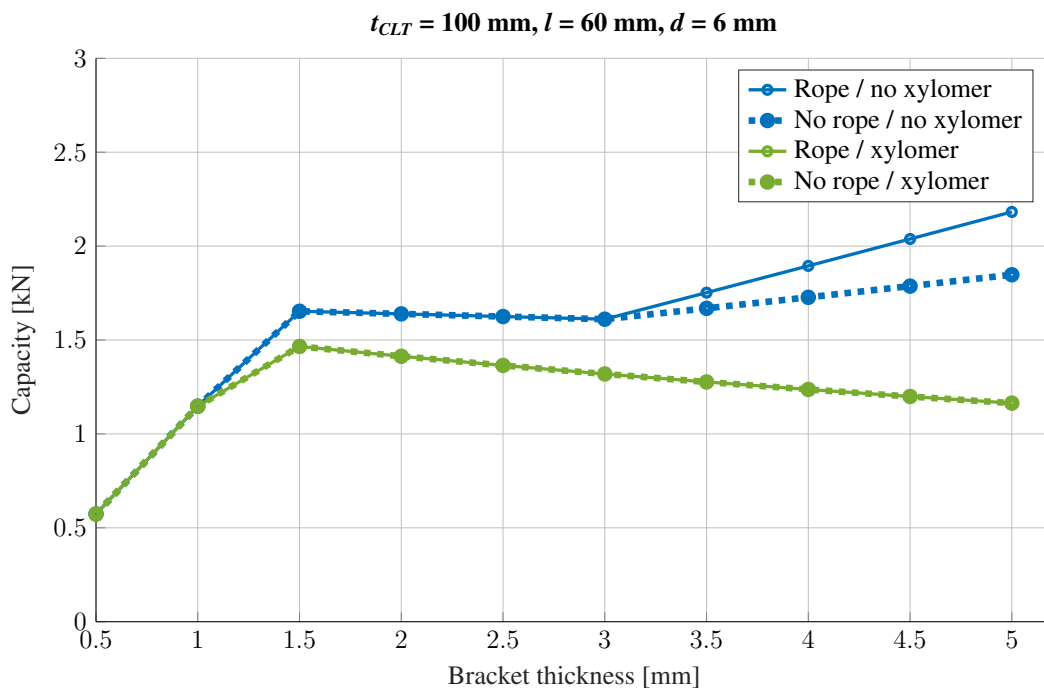


Figure 4.11: Load-carrying capacity for a 60 mm long fastener with 6 mm diameter and varying plate thicknesses, with a CLT thickness of 100 mm. The curves represent different configurations considering the presence of the rope effect and xylomer.

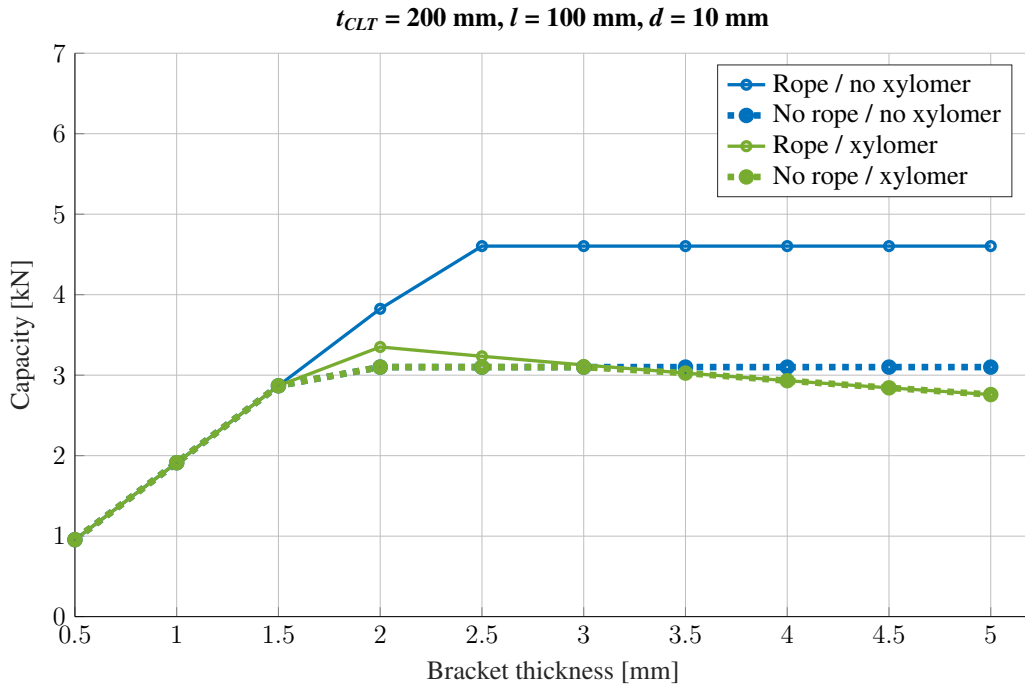


Figure 4.12: Load-carrying capacity for a 100 mm long fastener with 10 mm diameter and varying plate thicknesses, with a CLT thickness of 200 mm. The curves represent different configurations considering the presence of the rope effect and xylomer.

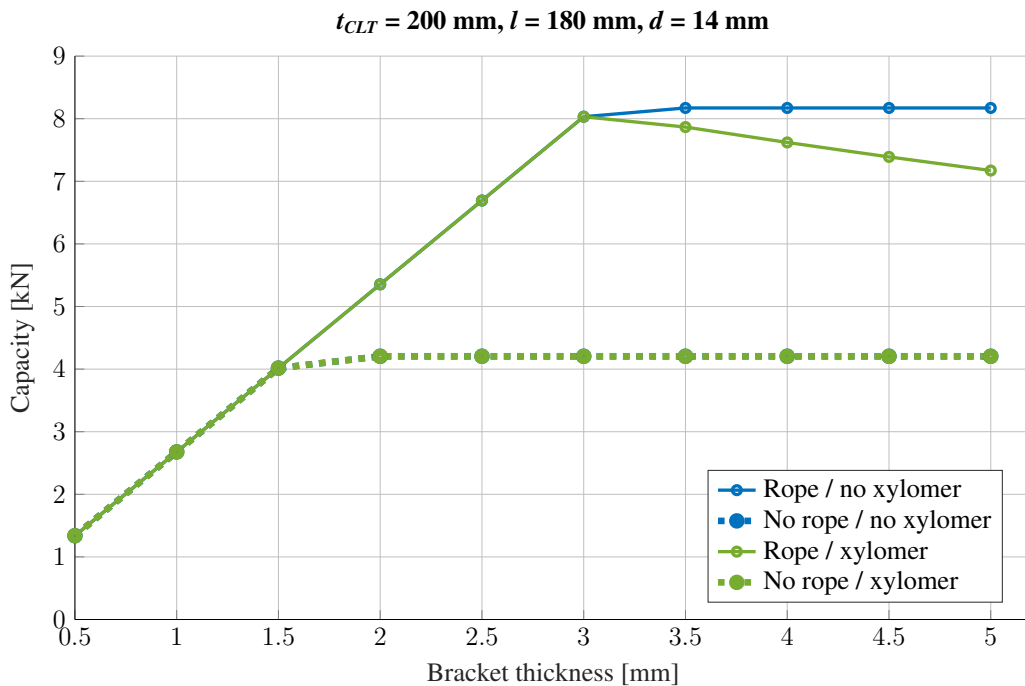


Figure 4.13: Load-carrying capacity for a 180 mm long fastener with 14 mm diameter and varying plate thicknesses, with a CLT thickness of 200 mm. The curves represent different configurations considering the presence of the rope effect and xylomer.

4.3 Optimization

Tables 4.3-4.6 show the optimized shear brackets that fulfill the constraints defined in Section 3.3.3 for the different CLT wall-to-floor configurations, considering the effects of both the rope effect and xylomer. In these tables, the first two columns are the wall and floor thicknesses, respectively, in [mm]. The cost is listed in [SEK], and the number of fasteners is denoted by n . The other parameters are screw diameter (d), screw length (l), bracket width (B), bracket depth (P), bracket height (H), and bracket thickness (S), which all are in [mm]. There, it can be seen that the most optimal connection configuration is constant within each wall configuration, i.e., with wall thickness constant and floor thicknesses varying. In the case shown in Table 4.3, where the rope effect is included and xylomer is excluded, an increase in wall thickness results in a longer screw length in the wall and a larger screw diameter in the floor. However, it also leads to a shorter screw length in the floor and a reduced number of screws in both the wall and floor. The reduction in number of screw also mean a reduction in bracket width. In Tables 4.3 and 4.4, it can be noted that the number of fasteners in the cases with xylomer is either larger in diameter or increased in number, and thus the length decreases. In Tables 4.5 and 4.6, it can be noted that no feasible solutions can be found that satisfy the set constraints, in the case when the CLT-wall is 100 mm thick. Moreover, for the 140 mm thick wall, it can be seen that the xylomer won't affect the solution and that it's viable for both cases. Lastly, it can be observed that the cost of the different considerations regarding the rope effect and xylomer, along with the different CLT wall-to-floor configurations, doesn't vary significantly.

Table 4.3: This configuration includes the rope effect but excludes xylomer.

Wall	Floor	Wall			Floor			Bracket				Cost [SEK]
		d	l	n	d	l	n	B	P	H	S	
100	160	10	80	6	8	140	5	89	63	53	2.5	61
	180	10	80	6	8	140	5	89	63	53	2.5	61
	200	10	80	6	8	140	5	89	63	53	2.5	61
140	160	10	100	4	10	100	4	73	63	63	2.5	59
	180	10	100	4	10	100	4	73	63	63	2.5	59
	200	10	100	4	10	100	4	73	63	53	2.5	59

Table 4.4: This configuration includes the rope effect and xylomer.

Wall	Floor	Wall			Floor			Bracket				Cost [SEK]
		<i>d</i>	<i>l</i>	<i>n</i>	<i>d</i>	<i>l</i>	<i>n</i>	<i>B</i>	<i>P</i>	<i>H</i>	<i>S</i>	
100	160	10	80	6	10	100	5	89	63	63	2.5	65
	180	10	80	6	10	100	5	89	63	63	2.5	65
	200	10	80	6	10	100	5	89	63	63	2.5	65
140	160	10	80	6	10	80	6	137	63	63	1.5	58
	180	10	80	6	10	80	6	137	63	63	1.5	58
	200	10	80	6	10	80	6	137	63	63	1.5	58

Table 4.5: This configuration excludes the rope effect and xylomer.

Wall	Floor	Wall			Floor			Bracket				Cost [SEK]
		<i>d</i>	<i>l</i>	<i>n</i>	<i>d</i>	<i>l</i>	<i>n</i>	<i>B</i>	<i>P</i>	<i>H</i>	<i>S</i>	
100	160	-	-	-	-	-	-	-	-	-	-	-
	180	-	-	-	-	-	-	-	-	-	-	-
	200	-	-	-	-	-	-	-	-	-	-	-
140	160	10	80	6	10	80	6	137	63	63	1.5	58
	180	10	80	6	10	80	6	137	63	63	1.5	58
	200	10	80	6	10	80	6	137	63	63	1.5	58

Table 4.6: This configuration excludes the rope effect but includes xylomer.

Wall	Floor	Wall			Floor			Bracket				Cost [SEK]
		<i>d</i>	<i>l</i>	<i>n</i>	<i>d</i>	<i>l</i>	<i>n</i>	<i>B</i>	<i>P</i>	<i>H</i>	<i>S</i>	
100	160	-	-	-	-	-	-	-	-	-	-	-
	180	-	-	-	-	-	-	-	-	-	-	-
	200	-	-	-	-	-	-	-	-	-	-	-
140	160	10	80	6	10	80	6	137	63	63	1.5	58
	180	10	80	6	10	80	6	137	63	63	1.5	58
	200	10	80	6	10	80	6	137	63	63	1.5	58

5 Discussion

This section aims to discuss the results more thoroughly, combining findings from the literature review, interviews, parametric study, and optimization. Moreover, answers for the research questions will be provided.

5.1 Key factors affecting reusability

To address the first research question regarding what factors affect the reusability of CLT connections, this study combined insights from industry interviews with the findings in Section 2.1. While the strategy of DfR is a good way of reducing raw material use and lowering emissions, its application is non-existent in Sweden for CLT panels. This appears to be due to the lack of reliable methods for the strength verification of reused CLT elements, along with the logistical problem of identification, tracking, and storage of the elements. Moreover, the variation in connection types used in the industry highlights the need for establishing standard connection solutions. This variation complicates the disassembly process and hinders the development of reusable systems. These findings indicate that improving the reusability of CLT structures requires not only technical solutions but also procedures for strength verification and logistics of the CLT panels.

The interviews also show that the only connection type possible to disassemble in a fairly easy manner, without damaging the CLT element, is a screwed bracket connection. This because long construction screws and nails are hard to disassemble without damaging the CLT element, and a bolted bracket (as in Figure 3.1d) being inconvenient to assemble. Furthermore, the results show that the screwed bracket connection should be designed with fewer and larger screws due to fewer screws being faster to install and larger screws not breaking as easily when unscrewing as for the smaller screws.

As discussed in Section 2.4, different failure modes - specifically failures in the timber, steel brackets, or fasteners - can have different impacts on the potential for reuse of structural components. If the failure occurs only in the timber, with no deformation in the fastener, disassembly is possible. If the failure is in the fastener, the disassembly process can range from difficult to impossible, depending on the extent of the deformation. When the failure occurs in the steel bracket, the connection can be disassembled as long as the screw remains undeformed. Furthermore, it's mentioned in Section 2.1 that when designing according to DfR, the ability to predict and control damage of the elements is a key aspect for reuse. This is typically done by letting plastic hinges form in the fasteners, as this gives a ductile and predictable failure. However, since failure in the fastener would make it nearly impossible to disassemble and the associated timber failures are more brittle, this means that a failure in the bracket is the most preferable. Therefore, a shear connection designed for reuse of the CLT element should be a screwed bracket connection, with fewer and larger screws, failing in the bracket, i.e.,

failure modes h and i in Table 4.2.

5.2 Consideration of plastic deformation

An important aspect to note is the increase in capacity due to the rope effect once the fastener begins to deform, as described in Section 2.4.1.3. This means that even when the ultimate failure occurs in the bracket (i.e., failure modes h and i in Table 4.2), the fastener may still have undergone yielding and plastic deformation. As a result, the calculated capacity of the connection may not accurately capture its actual deformation behavior. The calculated capacities for failure modes b , d , and e include a contribution of up to twice the capacity calculated based on the EYM. This contribution arises due to the yielding of the fastener, which results in permanent deformation.

To account for this, the continuation of this study first examined the use of an overstrength factor, as explained in 2.4.3, to control the governing failure mode by ensuring that the capacities involving yielding in the fastener, scaled by this factor, exceed the bracket-related failure modes. At first glance, this can be seen as a good approach, but it was realized, however, that due to only the ultimate capacity being multiplied by the factor, it did not take the amount of post-yield strength gained into account. This means that when using this factor on screws of varying size, there will be a lot of volatility in the results. In figure 5.1, the difference in capacity between a 90 mm screw and a 150 mm screw can be seen, taken from tests done by Ling et al. (2021). It can be seen that in a connection where the yielding strength is more or less equal to the ultimate strength, as in figure 5.1a, the capacity will be underestimated, whilst when there is more post-yield strength gains, as in figure 5.1b, the capacity might be overestimated. Because of this, the approach of using an overstrength factor was discontinued.

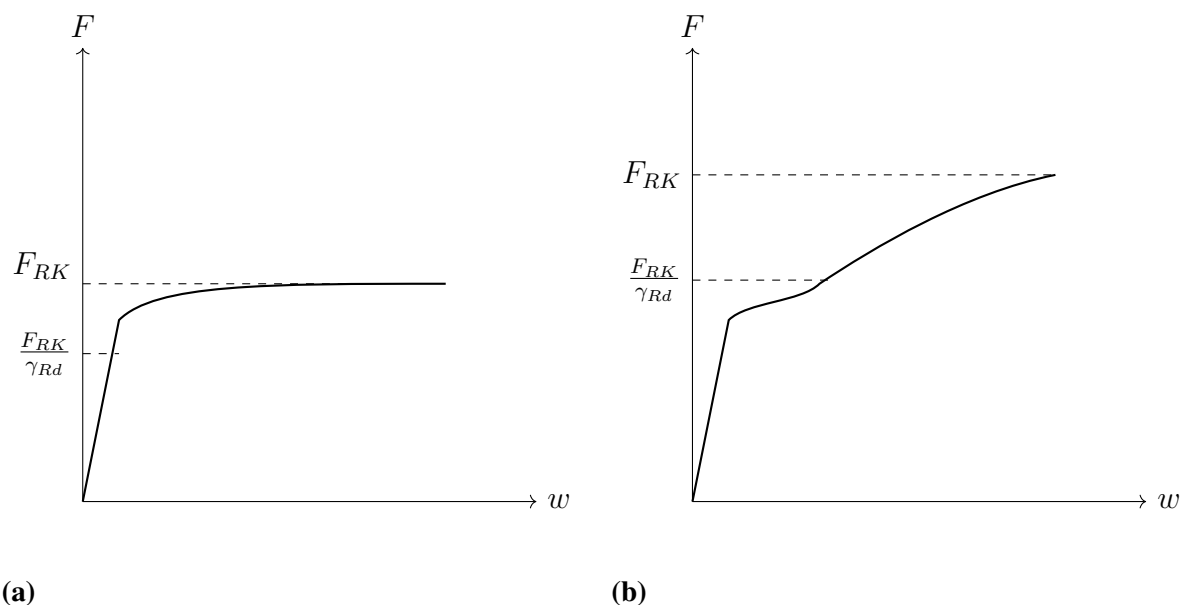


Figure 5.1: Difference between applying an overstrength factor on a 90 mm screw (a) compared to a 150 mm screw (b), own illustration based on (Ling et al., 2021).

Instead, the focus was shifted back to the rope effect and how it's added onto Johansen's equations. As mentioned in section 2.4.1.3, the rope effect corresponds to the gained capacity due to yielding of the fastener. Therefore, to account for plastic deformation in the fastener, the rope effect is simply disregarded. This results in lower capacities for some of the failure modes containing the rope effect (b , d , and e) but will ensure that the fasteners remain in the elastic region. This way, only connection configurations that have sufficient capacity and no yielding of the fasteners can be found.

5.3 Impact of connection configuration on failure modes

The second research question regarding how different combinations of fasteners and brackets influence the response of a CLT connection was addressed through the parametric study presented in Section 4.2. As concluded earlier in the study, the only fastener type of interest in designing a demountable connection are screws, thus only screwed connections were further analyzed. The results show that, regardless of screw diameter and length, the capacity increases approximately linearly up to a certain bracket thickness, typically between 1.5-3 mm, beyond which the capacity tends not to vary significantly. Similarly, when looking at the required number of fasteners needed to achieve the capacity from the case study in Section 3.2, it decreases up to a certain bracket thickness, typically between 2-4 mm, beyond which the number of fasteners tends not to vary significantly. For both cases, i.e., when looking at the capacity per fastener and required number of fasteners needed to achieve capacity, respectively, this threshold varies with screw geometry, with longer screws corresponding to the upper end of the thickness range. Up to this threshold, the failure mode is in the bracket, i.e., failure modes h and i in Figure 4.1, and beyond this threshold, the governing failure mode is either in the timber, fastener, or a mix of both.

The difference in the threshold values is due to the failure mode i being dependent on the bracket geometry, which, when calculating the capacity per fastener, is not determined yet. This means that the interaction between the screw and bracket parameters cannot be fully captured unless the bracket geometry is defined. As a consequence, when looking at the capacity per fastener, they might not yield the actual governing failure mode of a complete connection.

The reason the governing failure mode is always being in the bracket for thicknesses below the threshold is that the shear area of the bracket, A_v , is directly proportional to the bracket thickness, S . For bracket thicknesses above this threshold, the resulting capacity becomes greater than the capacity associated with the other failure modes, i.e., failure mode $a-g$ in Table 4.2.

An unexpected observation is that for a CLT slab thickness of 100 mm, the capacity per fastener for 8 mm-diameter screws tends to exceed the capacity for 10 mm-diameter screws with an increasing bracket thickness, as can be seen in Figure 4.4. This is due to the difference in the effective length of the screws, which affects the calculation of embedment strength and, consequently, the overall capacity. This is due to Eurocode

5's (2004) lack of covering the design of CLT. Throughout this project, the CLT handbook (2017) has been used to calculate the connection capacity. This handbook only provides partial coverage of the necessary calculations. For example, when certain parameters, such as if the effective length of the screw covers three board layers and the screw diameter is above 6 mm, are fulfilled, the CLT handbook provides an equation for calculating the embedment strength. When these parameters are not fulfilled, it states that Eurocode should be used instead. The CLT handbook's way of calculating the embedment strength always yields a lower strength than Eurocodes' way of calculating it. Thus, when the screws are longer, with longer effective length, the embedment strength will be reduced.

Another, more expected, observation is that when the rope effect is excluded from the per-fastener capacity calculations, the capacity is lowered when the bracket thickness is above 1.5 mm. Below this thickness, the governing failure mode will be in the bracket (h) due to the shear area, A_v , not being sufficient for smaller thicknesses. It also appears that the rope effect becomes more significant, i.e., the difference between the capacity with and without rope effect increases, for screws with a high length-to-diameter ratio. The reason for this is that longer screws allow more axial displacement, enabling greater tensile forces, and thereby increasing the contribution of the rope effect (Isaksson et al., 2022; Jockwer, 2024c). This is most notable for the most slender and thick screws, respectively. For the intermediate slenderness, the relation between the length-to-diameter ratio and the impact of the rope effect is not as clear, which might be due to what failure mode that is governing. This is because only failure modes b , d , and e in Table 4.2 are influenced by the rope effect; the others aren't, and thus the comparison becomes inconsistent when evaluating total capacity across all modes, as not all failure modes benefit from the additional strength provided by the rope effect. It might also be due to the calculation of the withdrawal capacity since the length has a greater impact than the diameter. Thus, screws with the same length-to-diameter ratio might show different relative capacities with and without the rope effect, depending on their absolute lengths. However, from this it is clear that longer screws have higher capacity, but a large portion of the capacity comes from the rope effect, and thus the fasteners might have started to yield, resulting in permanent deformation, even if the failure mode is such that it should not happen. This phenomenon was shown in the results presented in Section 4.2, where a connection configuration initially indicated a bracket failure mode (h) as governing. However, when checking that same configuration without the rope effect, the governing failure mode shifted to the fastener (b). This indicates that yielding of the fastener can still occur, even when the ultimate failure is governed by the bracket.

Regarding the impact of xylomer on the connections, the results show that it has a greater reduction of capacity for smaller screws concerning their length and diameter. This might be due to the bending failure of the fastener, i.e., failure mode g in Table 4.2, being being proportional to the cube of the screw diameter. As a result, even small changes in screw diameter have a significant impact on the bending failure capacity of

the screw. Another observation made is that when xylomer is included, the rope effect has little to no impact on the capacity for smaller screws, i.e., screws with a diameter less than 10 mm. For larger screws there is a reduction in capacity that matches the length-to-diameter ratio reduction as previously mentioned. The reason for this is that for smaller screws, the bending failure of the screw, i.e., failure mode g in Table 4.2, is governing. This capacity is not only proportional to the cube of the screw diameter, but is also influenced by the xylomer thickness, which increases the eccentricity and thereby also increases the bending moment acting on the screw.

5.4 Reflections regarding the optimization process

As concluded in Section 5.1, a shear connection designed for reuse should be a screwed bracket connection, with fewer and larger screws, failing in the bracket. It also emerged that standardization is key for reusability, whereby the constraints B_{limit} and B/P_{ratio} were used in the GA as described in Section 3.3.3. These constraints ensured that the generated connection configuration was always of reasonable dimensions. The values of these were generated from the case study in Section 3.2, as well as the design load on the wall to be studied. The number of brackets to transfer the load was arbitrarily chosen to be four. However, this could also have been an input parameter in the GA.

In section 5.3, it appeared important to consider the full connection configuration, and not only the per-fastener capacity, due to the risk of not capturing every possible failure mode. Thus, the GA calculated the full connection capacity and its governing failure mode, along with its price. Regarding the cost of the connection, it includes only the material cost, i.e., screw and bracket costs, respectively. The labor cost was excluded due to the difficulty in accurately estimating the required assembly time for the different connection configurations. However, since a reusable connection should be designed using fewer and larger screws, an optimization factor, as defined in Equation 3.6, was introduced. This approach gives the number of screws, N , a greater influence on the optimization factor than the price itself. This is because the price already accounts for the cost per screw, and while the price difference for a single screw is relatively small, increasing N significantly amplifies the value of the optimization factor of the connection. An alternative approach would be to redefine the objective functions of the GA to include two objective functions, instead of one, namely *Price* and the number of fasteners N . These could then be weighted relative to each other to guide the optimization process.

The result in Section 4.3 shows that when xylomer is used, the most optimized connection configuration uses shorter and larger diameter screws. The reason for this is that the screw bending capacity is highly dependent on the screw diameter, and thus increasing the screw length is inefficient. Longer screws are also more expensive than the shorter ones, which further supports the choice of choosing shorter screws. It was also shown that the cost didn't vary significantly between the different configurations of wall and floor thicknesses or when considering the xylomer and the rope effect. This might be

due to the labor costs not being included in the calculation of the total cost.

An unexpected observation is that for the case when the rope effect is excluded, there is no possible connection configuration for the 100 mm thick wall within the defined constraints, and screw input, of the GA. As can be seen in Tables 4.5 and 4.6, there are possible configurations for the 140 mm thick wall. The reason this configuration not working for the 100 mm thick wall is that the effective length of the screw, and the layer thickness of the different wall thicknesses, is such that the embedment strength will be calculated differently, and thus lowering the capacity for the thinner wall. It can also be seen that the generated solutions for the 140 mm thick wall are the same. This is because, as stated in Section 5.3, a screw with a high length-to-diameter ratio, i.e., a long screw, loses a big portion of its capacity when excluding the rope effect. Since no possible connection configurations were found for the 100 mm thick wall, and the generated configurations for the 140 mm thick wall are the same in the cases where the rope effect was excluded or both the rope effect and xylomer were included, it suggests that the rope effect has a greater influence on the results than adding xylomer.

A clear connection can be seen between the results from the GA in Section 4.3, and the parametric study in Section 4.2. It was shown that a connection without rope effect, as in Tables 4.5 and 4.6, yields the same configuration, regardless of the xylomer. The same phenomenon was observed in Figures 4.11-4.13, where the impact of xylomer, with the rope effect excluded, on the per-fastener capacity was minimal. This further supports the validity of our calculations.

5.5 Design and reuse of CLT panels

The critical factors to be considered in the design of a connection to enable the reuse of CLT panels are:

- Use only a screwed bracket connection.
- Use standardized connections.
- Design for fewer and larger screws, and the bracket to have a thin plate.
- Design for failure in the bracket, with the rope effect excluded to ensure no deformation in fasteners.
- With xylomer, for larger screws, the design remains the same as when excluding the rope effect.

As emissions from the construction industry are high, and prices are expected to rise with increasing usage of timber, methods to battle this have to be developed. This thesis focused on the CLT connections and how they can be designed for the ease of disassembly while still being economically and structurally sound. This will allow using the CLT as one wants to, either reusing it in another setting or just for easy dismantling during demolition. Questions have arisen, however, on how the reassembly in the new setting would be performed. When successfully disassembled, screws will leave screw holes.

The theory and interviews agree that the reuse of the same screw holes is not preferred as the strength of the connection is hard to declare. This means that for reattaching a connection, unused CLT is needed. Therefore, moving the bracket sideways to an unused part of the CLT is an alternative when reusing. While this will allow several iterations of reuse, infinite reuses of the CLT will be impossible, as you eventually run out of space to place a new connection. This will, however, utilize the CLT further than it is being utilized today.

5.6 Further studies

The limitations in this thesis have left some gaps. During the work, attempts to determine methods for stiffness and ductility calculations of the proposed connections were conducted, but without success. It was found that designers of conventional CLT connections do some analytical analysis of their products for structural strength, but mostly design with the help of testing. It would therefore be interesting to test the proposed connections for strength, stiffness, and ductility. Furthermore, numerical models would be a good way to evaluate the deformation of the connections.

Due to assumptions made during the thesis, a narrow design space was created. With the knowledge of prices for assembly and disassembly, even more specific costs for each solution could be evaluated. Moreover, assumptions regarding the number of brackets which is needed to carry the case study load, and only using limited variations of steel material and xylomer thickness, made the design space even narrower. By expanding these parameters into variable parameters in the GA, even better solutions may be found.

In general, the findings regarding reusability in the interviews show that the industry requires not only technical solutions but also frameworks for verifying already existing CLT elements, logistics, and profitable business models. For these to appear, however, reasonable technical solutions have to be developed. It would therefore be interesting to investigate how screw holes influence subsequent connection in a CLT panel.

6 Conclusion

Reducing emissions in the construction industry is essential to reach the net-zero goals set by the European Union. The circular approach of reusability is an alternative to the linear design methods used today. This thesis aimed to investigate the reusability of CLT panels with a focus on the connection design. It was found that the key factors affecting reusability were the connection type and, more importantly, the kind of fastener used. Long construction screws and nails are not an alternative if a CLT panel is to be reused. Instead larger screws in a bracket configuration should be used. Standard solutions are another important factor. The respondents in the interviews pointed out how connections vary significantly today, and the need for a simple and uniform system would ease the reuse process.

Different failure modes affect the reuse potential. Failure in the screw will result in damaging the CLT panel as well as significantly complicate the disassembly process. Failure in the timber will result in the screws being easy to disassemble but the panel will still take a lot of damage. It is therefore preferred to have failure in the bracket as this limits damage in the CLT, doesn't deform the screw, while also being a more ductile failure.

Generally, for thin brackets, i.e., thicknesses of 1.5-2 mm, the bracket will always fail. However, if the rope effect is excluded, the governing failure mode will in some cases shift towards failure in the screw instead of the bracket. This highlights the importance of considering it due to the screw starting to yield before reaching its ultimate capacity. For thicker brackets, the failure varies between failure in the timber, screw, or a mix of both. If xylomer is added, the failure will exclusively be bending failure of the screw, as this induces an eccentricity of the load, leading to a large bending moment of the screw.

Optimizing the connection for cost and reusability generally yielded configurations with few screws that were larger in diameter and shorter in length. However, when excluding the rope effect, no possible solution could be found within the set constraints for wall thicknesses of 100 mm. This seems to be because Eurocode and the CLT handbook use different formulas for calculating the embedment strength.

Lastly, this thesis has provided knowledge about the technical aspects of the CLT connections. It was apparent from both the literature study and the interviews that more development are needed, mostly regarding the logistics behind reusable CLT panels as well as finding sustainable business models that balance reduced emissions with economic profitability.

7 References

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A Interview with respondent 1

How do you work with disassembly?

Respondent 1 says that there is a significantly higher chance of disassembling a joint if fittings with screws are used instead of nails. Fitting screws can be easily disassembled after 50 years. If a joint consists solely of screws, it is common for the screw heads to be countersunk into the wood, which makes it difficult to locate them as the wood swells over time. The respondent describes a project where a CLT wall was to be moved and all screws except one were disassembled. This complicated the move as the crane could not pull out the screw. Joints with only screws require longer screws, which leads to difficulties during assembly and disassembly. This is because it is difficult to screw completely straight, the wood contains knots, and the screw is driven in with a lot of force and heats up. This melts the wood lignin and hardens around the screws, making the screw sit even tighter than originally. When the screw is then to be disassembled, the screw head breaks off due to the strong torque required.

Other problems that arise are if the screw has been mounted incorrectly. The respondent mentions that it is common for screws to be over-tightened for a connection with steel fittings. The screw head has already started to break off and when the wood then swells due to moisture variations, the screw head breaks off completely. The respondent refers to tools that prevent this (preset torque).

It also appears that larger and fewer screws are easier from a disassembly perspective, both in execution and time-wise. Large screws are easier to handle, e.g., with gloves, and they are more durable.

How can one work with the reuse of CLT today?

Respondent 1 says that it is not possible to screw a new screw into an old hole, so it is better to move the fittings to new, fresh wood. CLT is good in that you have a lot of surface area to screw into. Furthermore, the respondent says that if a CLT wall is to be reused, one solution could be to leave the fittings in the wall. However, this can entail difficulties with optimization as the wall/fittings have a determined capacity, which must match the new application.

How do you verify the condition/capacity of connections during reuse?

If someone wanted to reuse connections, they would probably take one of the connections and test it to determine its capacity.

What do you think hinders reuse?

Respondent 1 says that the variety of different fastenings in a building has a significant impact on reuse. It is also evident that knowledge during assembly can be lacking, as regular carpenter screws and CLT screws need to be mounted in different ways. Furthermore, the respondent says that another obstacle is that suppliers' product data only applies to new fittings.

What do you think should be done to promote reuse?

To promote reuse, Respondent 1 believes that suppliers need to be required to report capacities and safety factors during reuse, as long as the building has not suffered from rot or partial collapses where fittings have been consumed. It is also mentioned that standardization is an important component to promote reuse, for example, by removing different variants of fastenings and finding more uniform connections. The respondent

believes that this will bring efficiency. Furthermore, the respondent prefers the use of fittings and steel plates in connections to avoid having to search for hidden screw heads. It is also important that the assembly of fittings and screws is done correctly.

How can you guarantee that a reused element has the same capacity?

Suppliers of fastenings would need to report, for example, a reuse coefficient to adjust the capacity. They must obtain a certificate/guarantee in some way that the initial assembly was done correctly.

How are the properties of CLT affected by reuse (assembly, disassembly, and re-assembly)?

Respondent 1 says that cracks can start to form in the wood and that the wood swells due to moisture. Furthermore, the respondent says that for CLT, there is no concern as the elements are large, and there are opportunities to move connections during reassembly. This leads to less optimization of the current load case as, for example, hold-downs depend on force pairs.

B Interview with respondent 2

How do you work with reuse? Do you have any experience with reusing CLT panels?

Respondent 2 says that reuse of CLT elements has not yet occurred in Sweden, but the question is being asked by their customers.

What prevents us from reusing, for example, a CLT wall?

The logistics in the industry are not adapted for the reuse of CLT elements. A newly manufactured CLT panel is strength-tested, which is necessary for certificates that ensure the manufacturing has been done in a quality-assured manner to be valid. This is so that designers can retrieve table values for CLT elements.

The construction industry must be able to quality-assure and evaluate the performance of load-bearing products, such as CLT panels, for reuse to be possible. Today, there are no such methods/industry standards. Other logistical challenges include incorporating information about what a CLT panel was once specified for, through for example, digitization and a digital twin. Additionally, the storage of reused CLT elements must be managed.

Today, reuse (storage and control) of CLT elements is not feasible from an economic perspective. Handling reused CLT elements must not increase costs. Something needs to be done to make it cheaper to, for example, dismantle panels. For instance, a penalty system for handling new raw materials provides an incentive to use reused material. Another problem is the question of who will be responsible for reused material in the future, i.e., who will take back and quality-assure the material?

When reusing CLT panels, what must be taken into account? (Holes, deformations in the panel, etc.)

A screw can be unscrewed if it has been in place for a short time, but 50 years into the future, it will be a challenge to remove them. It is mentioned that wood has long-term effects that we need to understand better. In walls, Respondent 2 does not see that long-term effects would affect much, but more in floors.

It is also noted that no CLT building has stood for 50 years yet, so the effects cannot be seen yet. However, the respondent does not believe that the wood material will be affected much if it has been handled correctly during assembly and moisture impact. The respondent is a bit unsure about the glue that bonds the lamellas in CLT panels but receives no indications from glue suppliers that the glue has a lifespan.

Do you see any disadvantages with a bolted joint? Would the wood be negatively affected by having larger but fewer holes?

If the static calculations hold, the respondent does not see any problem with bolted joints. On the contrary, it is considered an advantage as these lead to fewer, larger, and more robust fastenings, which facilitate assembly. Disassembly also becomes easier as the joints are easy to find, even after 50 years. It is more common to use many small screws that remain hidden, and these are comparatively very difficult to access.

There are pros and cons to both options. For a joint with fewer and larger elements, there is not as much to handle. However, large screws are heavy to install as different equipment is required, such as a larger screwdriver and jig to mount straight. Since

the screwdriver is so strong, a stand is needed. This means you cannot screw in all directions because it is so large and cumbersome. There is also a work environment aspect to consider. For a joint with many smaller fasteners, there is well-developed screw and nail technology, e.g., nail guns are fast, and the machine is very light. In the end, to achieve the most time- and cost-effective assembly possible, many aspects come into play.

How are the properties of CLT affected by reuse (assembly, disassembly, and re-assembly), and how is this considered in dimensioning? (k_{mod} , safety factors, downgrading of wood quality)

The respondent believes that factors such as k_{mod} , the downgrading of wood quality, and other safety factors are aspects that can be used in dimensioning for reuse. For each new life cycle, the quality/classification of the wood can be lowered, for example, to avoid overutilization.

Are there industry standards that affect the possibility of reuse?

Today, there is no standard or agreed-upon strategy in society for applying the reuse of CLT elements. Society must choose an approach at a larger/political level. Only when a reward or penalty system is introduced will incentives for reuse take off, as no builder will voluntarily want to pay much more for their house by using reused material.

A standard similar to that for steel is essential for reuse to work. Regulations need to be established in some way. Based on the regulations, an infrastructure can be created.

With today's theories and rules, you cannot reuse either screw holes or the same screws as safety comes first. Both the wood and the screws can have altered properties after assembly, which means that the structural capability cannot be guaranteed.

Other

To find infrastructure for reuse, standardizations are needed. Every new project chooses to solve connections in new ways. By standardizing connections, the efficiency in new construction can be increased while reuse can be facilitated. For example, a standardized instruction on how a CLT wall-to-wall connection is mounted can be established. Then you don't have to archive documents/information because it is standard which connection is used. Then, fewer variants of connections need to be found as a solution for reuse. Robust, simple, and intuitive solutions are preferred.

C Interview with respondent 3

Do you have experience in dismantling CLT elements?

The only experience Respondent 3 has with dismantling is during the actual assembly, where something went wrong, and they had to redo the execution. It is also mentioned that a pavilion at the World Expo in Dubai was designed with dismantling in mind.

- **What does the process look like?**

The work should be done in reverse order. It is important to demolish in the correct order and to brace during the process. It is simple from the perspective that you don't need to think about how flat, horizontal, and straight it is. However, there are many other things that need to be removed before the wood can be dismantled, such as the facade and insulation. The dismantling must be done in a way that does not damage the wood. There must be a plan for how to access/release a connection considering screws that cannot be unscrewed.

What complicates the process?

It will not be possible to unscrew all screws as they are not designed for it. Large construction screws that tighten hard during assembly, combined with the settling of houses over time, risk the heads breaking off. Additionally, the resistance to unscrewing a screw increases the longer it has been in the wood. The respondent has had problems with screws that cannot be dismantled and has had to insert a saw blade between the elements to cut off the screw, as it is not possible to separate the panels if construction screws remain.

The respondent has never experienced any problems with dismantling screws. They have needed to move this type of fitting. It is fiddly, but not a problem. It is easier to use more plates and angles instead of construction screws.

What happens to what you dismantle? CLT, fittings, etc.?

Fittings and CLT panels are seen as potentially reusable as they have not incurred significant damage. However, minor repairs may be needed on CLT panels at visible surfaces for aesthetic reasons. Screws cannot be reused as the heads are likely to break off during reassembly.

Do you have experience with deformed connections and their dismantling?

The respondent does not have much experience with dismantling deformed screws and fittings. They have only dismantled connections after they have been in the panel for a short time. However, problems arise with construction screws where two CLT panels have been joined. These can shift sideways relative to each other and create shear forces in the screw, causing the screws to seize. Combined with the swelling of the wood, the screws become very difficult to dismantle.

With the way things are assembled today, how easy do you think it will be to dismantle?

Construction screws make it very difficult and are potentially a big problem. It will take an incredibly long time to remove elements if you cannot dismantle the screws, while also being careful with the wood. Additionally, no one will want to handle a CLT panel that risks having old steel in it.

- **What types of connections do you think are easy/difficult? Why are some**

more difficult than others? (nails, screws, bolts, number, size, etc.) When do screws or bolts become too large to handle (force and tools)?

Construction screws are a problem when dismantling. Partly because they will be difficult to find as the heads are hidden in the wood (e.g., from moisture during construction that causes the wood to swell) and partly because long and thick construction screws are very heavy to handle. You need machines that can handle this and a person to hold it, which is very heavy.

The respondent mentions that it is very difficult to dismantle a nailed connection. The fitting will probably be destroyed as you likely need to pry between the wood and the fitting, which also damages the wood. There is a risk that the nail heads even need to be sawed off.

It is much faster to assemble larger and fewer screws compared to many and smaller ones.

How would you change the design to maximize reuse?

Avoid construction screws and focus on designing joints/connections so that they are easy to dismantle. It is better to use angles or plates to avoid using construction screws. In designs where the floor hangs on the wall, angles should be used instead of construction screws. In designs where the floor lies on top of the wall, they are often toe-screwed together and then covered by the wall above. There, a flat plate could be placed on the outside instead to transfer forces between floors and walls. Fittings should preferably be designed with fewer and larger screws to facilitate dismantling. Ideally, special solutions regarding fastenings should be avoided.

What are the most common fittings/connections when you mount CLT walls to floors?

When mounting CLT walls to CLT floors, construction screws at an angle and angle brackets are primarily used. These can look different and have different designs, sometimes with reinforcing steel plates.

Other

- Good documentation so that this can be followed/projected..
- Generally, fastenings cost a lot of money. They estimate that fastenings cost 10% of the CLT wood cost.

Table C.1: Grading, from best to worst, of the connections due to different criteria in DEI. Connection A used nails, Connection B used smaller screws, Connection C used larger screws, and Connection D used a nut-and-bolt configuration. Brackets indicate that the grade is equal for the connection.

Criterion	Grading (Connection A to D)
Time	Assembly: A, C, D, B
	Disassembly: C, B, D, A
Tools	Assembly: (BC), A, D
	Disassembly: (BC), D, A
Fixture	Assembly: (ABC), D
	Disassembly: (BC), A, D
Instructions	Assembly: C, B, A, D
	Disassembly: C, B, D, A
Force	Assembly: B, C, A, D
	Disassembly: B, C, D, A
Hazards	Assembly: C, B, A, D
	Disassembly: (BC), D, A

DEI comments

Time:

The nail gun is large to carry around, and screwing is more controlled. The respondent prefers screwing, but nailing is faster. For the bolted joint (D), the holes in both elements cannot be prefabricated due to tolerances. It would be possible to prefabricate the holes in one panel and then drill the holes in the other. You need to bring an extra machine to drill the holes, and it probably requires two people to assemble. The respondent mentions that it might be possible to design a bolt that does not need a counterhold, making it possible to drive in a bolt and then go to the other side of the panel to screw on the nut.

For dismantling, larger screws are preferred. This is because the torx holes do not break as easily as on small screws, making them easier to unscrew. The respondent has never worked with a bolted connection but imagines that dismantling would involve unscrewing the nuts, tapping the bolt so it comes loose, and then either using a punch to drive out the bolt from the outside or using a special tool to pull out the bolt from the inside. Nails cannot be dismantled.

Tools:

During assembly, the respondent uses the same screwdriver for both large and small screws. Nail guns are used for nails, and a drill and bolt screwdriver are needed for bolts. The fact that screwdrivers are easier to handle than nail guns and the need for two types of machines (drill and bolt screwdriver) when assembling bolts determines the order.

During dismantling of nails, either the nails must be pulled out or the heads must be sawed off to release the fitting. In both cases, it is a destructive dismantling, and the respondent, therefore, considers nails unsuitable for dismantling.

Fixture:

During assembly, nail and screw connections are equivalent in terms of fixture as it is a one-person job. Bolted joints can also be a one-person job, depending on the design of the bolt. However, it can be difficult to access with machines if the distance between the hole and the element perpendicular to the hole is too small (the hole on the wall is too close to the floor, giving too little space to drill the hole straight).

During dismantling, the fixture is equivalent for both large and small screws, but not for nails as this requires more manual force, either to saw off the heads of the nails or to pry off the nails/fitting. For bolted joints, depending on the design, up to two people may be required.

Instructions:

The respondent has not used connection D, but it will require more training to make it efficient. The nail gun can be dangerous, and it is difficult to undo or correct if the fitting is misplaced, which increases the need for clear instructions. Large screws are preferred.

Removing nails is hot work, as you will need to saw. You must have a permit, training, and a fire extinguisher.

Force:

Use the same screwdriver for the two screw fittings. The nail gun is larger and heavier than the screwdriver. Fitting D requires the same machine we screw with, but it needs to be drilled. It can be heavy to drill depending on how thick the CLT wood is and how good the drill bit is, as it wears out quickly.

These screws do not settle over time (compared to construction screws). Noticeable difference between large/small screws, the large ones are heavier to drive in and out.

Hazards:

Fitting C is the quickest to install, making it the best choice since it's an uncomfortable position to work in. The respondent finds it difficult to comment on fitting D as he hasn't used it. With some uncertainty, it is placed last because it requires more steps and more machines.

Regarding disassembly, nails are the worst as the heads are sawed off, making it a hot job. Fitting B doesn't make much noise, and you don't need a large machine. Bolts are noisy and require force to drive through. Large screws require a larger machine that makes more noise, causing more strain on the arm and joints.

D Wind load

Wind load

The wind load of the building is calculated according to SS-EN 1991-1-4, and EKS 12

$\psi_0 := 0.3$ Partial coefficients,
EKS12, Table B-1

$\psi_1 := 0.2$

$\psi_2 := 0$

CONDITIONS

$h := 15 \text{ m}$ Building height

$\rho := 1.25 \frac{\text{kg}}{\text{m}^3}$ Density of air

$v_b := 25 \frac{\text{m}}{\text{s}}$ Reference wind speed in Gothenburg,
EKS12, Figure C-4

$q_b := \frac{1}{2} \cdot \rho \cdot v_b^2 = 0.391 \frac{\text{kN}}{\text{m}^2}$ EN-1991-1-4, Eq. 4.10

Table 4.1 — Terrain categories and terrain parameters

Terrain category	z_0 m	z_{min} m
0 Sea or coastal area exposed to the open sea	0,003	1
I Lakes or flat and horizontal area with negligible vegetation and without obstacles	0,01	1
II Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights	0,05	2
III Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest)	0,3	5
IV Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m	1,0	10

NOTE: The terrain categories are illustrated in A.1.

Terrain category III

$h = 15 \text{ m}$

Tabell C-10a Karakteristiskt hastighetstryck $q_p(z)$ i kN/m^2 på höjden z för, $v_b = 21\text{--}26 \text{ m/s}$ med $c_e(z)$ enligt 7 § och $\rho = 1,25 \text{ kg/m}^3$

v_b (m/s)	z (m)	Terrängtyp				
		0	I	II	III	IV
25	2	0,77	0,67	0,50	0,45	0,41
	4	0,90	0,81	0,64	0,45	0,41
	8	1,04	0,95	0,79	0,55	0,41
	12	1,13	1,04	0,89	0,65	0,45
	16	1,19	1,11	0,96	0,72	0,52
	20	1,24	1,16	1,01	0,78	0,58

EKS 12

$q_p := 0.72 \text{ kPa}$

Peak velocity pressure. Simplified by assuming it is constant over the height of the building. Conservative assumption of 16 m building height.

PRESSURE COEFFICIENTS AND LOADS

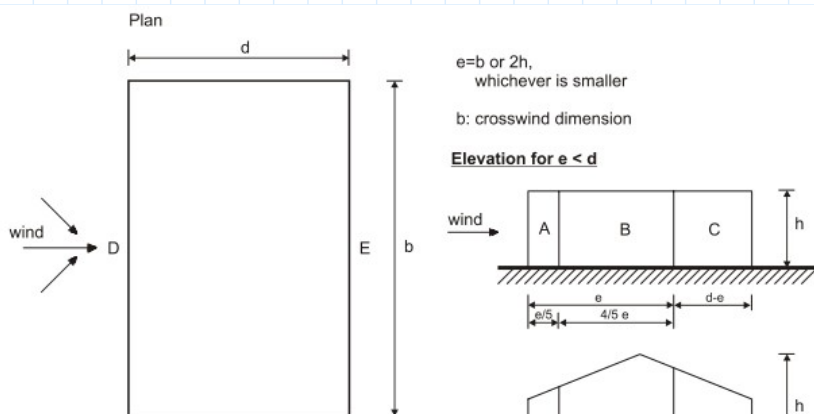
$b := 53 \text{ m}$

$D := b$

Building geometry

$d := 12.4 \text{ m}$

GEOMETRY according to SS-EN 1991-1-4 7.2.2



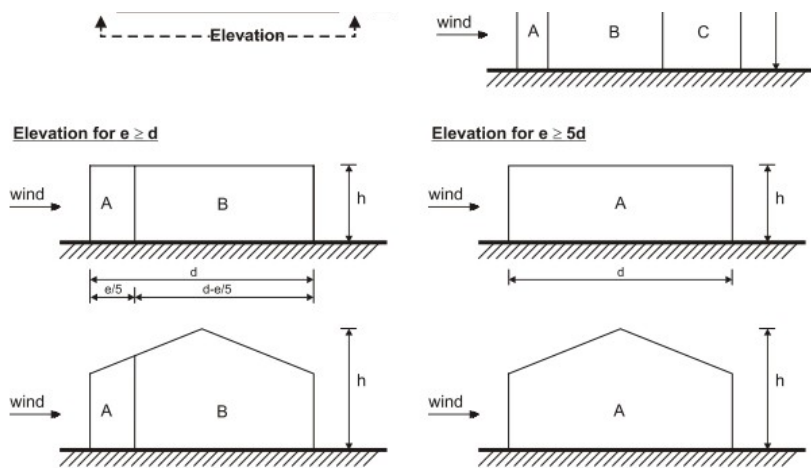


Figure 7.5 — Key for vertical walls

NOTE 1 The values of $c_{pe,10}$ and $c_{pe,1}$ may be given in the National Annex. The recommended values are given in Table 7.1, depending on the ratio h/d . For intermediate values of h/d , linear interpolation may be applied. The values of Table 7.1 also apply to walls of buildings with inclined roofs, such as duopitch and monopitch roofs.

$$h < d = 0$$

$$h < 2 \cdot d = 1$$

$$h < D = 1$$

$$h < 2 \cdot D = 1$$

$$e_y := \min(b, 2 \cdot h) = 30 \text{ m}$$

$$e_x := \min(d, 2 \cdot h) = 12.4 \text{ m}$$

$$e_y < d = 0$$

$$e_y > d = 1$$

$$e_y \geq 5 \cdot d = 0$$

$$e_x < b = 1$$

$$e_x > b = 0$$

$$e_x \geq 5 \cdot b = 0$$

$$\frac{h}{d} = 1.21$$

$$\frac{h}{D} = 0.283$$

Table 7.1 — Recommended values of external pressure coefficients for vertical walls of rectangular plan buildings

Zone	A		B		C		D		E	
	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$
5	-1,2	-1,4	-0,8	-1,1	-0,5		+0,8	+1,0	-0,7	
1	-1,2	-1,4	-0,8	-1,1	-0,5		+0,8	+1,0	-0,5	
$\leq 0,25$	-1,2	-1,4	-0,8	-1,1	-0,5		+0,7	+1,0	-0,3	

EXTERNALLY TOWARDS THE LONG SIDE

$$c_{pe.Ay} := -1.2 \quad \text{Suction} \quad q_{Ay} := q_p \cdot c_{pe.Ay} = -0.864 \text{ kPa}$$

$$c_{pe.By} := -0.8 \quad \text{Suction} \quad q_{By} := q_p \cdot c_{pe.By} = -0.576 \text{ kPa}$$

$$c_{pe.Dy} := 0.8 \quad \text{Pressure} \quad q_{Dy} := q_p \cdot c_{pe.Dy} = 0.576 \text{ kPa}$$

$$c_{pe.Ey} := -0.5 + (-0.7 - (-0.5)) \cdot \frac{\frac{h}{d} - 1}{5 - 1} = -0.51 \quad \text{Suction} \quad q_{Ey} := q_p \cdot c_{pe.Ey} = -0.368 \text{ kPa}$$

EXTERNALLY TOWARDS THE SHORT SIDE

$$c_{pe.Ax} := -1.2 \quad \text{Suction} \quad q_{Ax} := q_p \cdot c_{pe.Ax} = -0.864 \text{ kPa}$$

$$c_{pe.Bx} := -0.8 \quad \text{Suction} \quad q_{Bx} := q_p \cdot c_{pe.Bx} = -0.576 \text{ kPa}$$

$$c_{pe.Cx} := -0.5 \quad \text{Suction} \quad q_{Cx} := q_p \cdot c_{pe.Cx} = -0.36 \text{ kPa}$$

$$c_{pe.Dx} := 0.8 \quad \text{Pressure} \quad q_{Dx} := q_p \cdot c_{pe.Dx} = 0.576 \text{ kPa}$$

$$c_{pe.Ex} := -0.3 + (-0.5 - (-0.3)) \cdot \frac{\frac{h}{D} - 0.25}{1 - 0.25} = -0.309 \quad \text{Suction} \quad q_{Ex} := q_p \cdot c_{pe.Ex} = -0.222 \text{ kPa}$$

SS-EN 1991-1-4, ch. 7.2.2 (3)

(3) In cases where the wind force on building structures is determined by application of the pressure coefficients c_{pe} on windward and leeward side (zones D and E) of the building simultaneously, the lack of correlation of wind pressures between the windward and leeward side may have to be taken into account.

NOTE The lack of correlation of wind pressures between the windward and leeward side may be considered as follows. For buildings with $h/d \geq 5$ the resulting force is multiplied by 1. For buildings with $h/d \leq 1$, the resulting force is multiplied by 0,85. For intermediate values of h/d , linear interpolation may be applied.

$$\frac{h}{d} \geq 5 = 0$$

$$\frac{h}{D} \geq 5 = 0$$

$$\frac{h}{d} \leq 1 = 0$$

$$\frac{h}{D} \leq 1 = 1$$

$$c_{korr.y} := \left(0.85 + 0.15 \cdot \frac{\frac{h}{d} - 1}{5 - 1} \right) = 0.86$$

$$c_{korr.x} := 0.85$$

INTERNAL SS-EN 1991-1-4 7.2.9

$$c_{pi.to} := 0.2 \quad q_{i.to} := q_p \cdot c_{pi.to} = 0.144 \text{ kPa}$$

$$c_{pi.from} := -0.3 \quad q_{i.from} := q_p \cdot c_{pi.from} = -0.216 \text{ kPa}$$

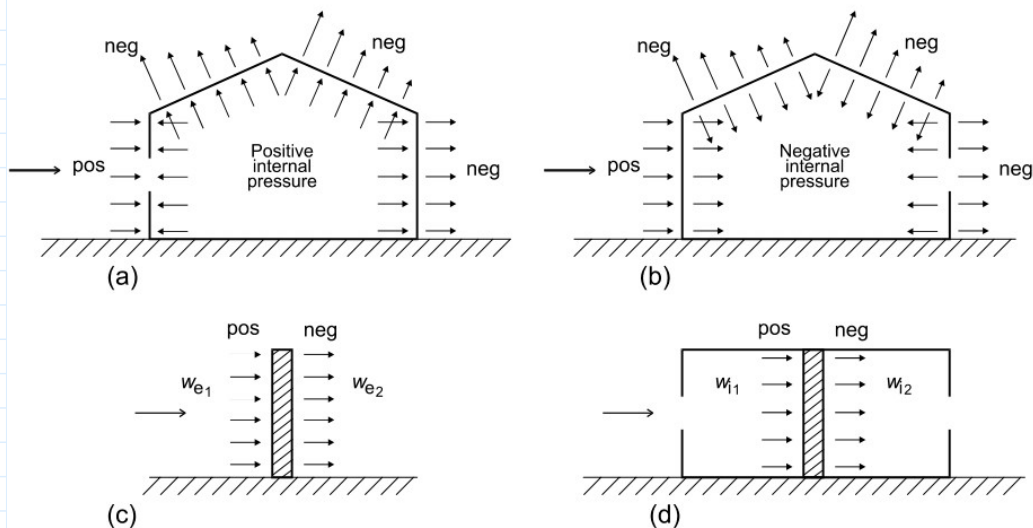


Figure 5.1 — Pressure on surfaces

GLOBAL :

$$q_{ky} := (|q_{Dy}| + |q_{Ey}|) \cdot c_{korr.y} = 0.809 \text{ kPa} \quad \text{Characteristic velocity pressure, long side}$$

$$q_{kx} := (|q_{Dx}| + |q_{Ex}|) \cdot c_{korr.x} = 0.679 \text{ kPa} \quad \text{Characteristic velocity pressure, short side}$$

E Hand calculations

Design of a CLT shear connector

Bracket geometry

$$B := 156 \text{ mm}$$

$$P := 55 \text{ mm}$$

$$H := 94 \text{ mm}$$

$$S := 2.5 \text{ mm}$$

$$p_1 := 39 \text{ mm}$$

$$p_2 := 32 \text{ mm}$$

$$e_1 := 15 \text{ mm}$$

$$e_2 := 15 \text{ mm}$$

$$d_0 := 10.5 \text{ mm}$$

$$n := 5$$

Number of fasteners in a row in the direction of the load (on one of the CLT panels)

$$n_{rows} := 2$$

Number of rows

$$\alpha_{load} := 90 \text{ deg}$$

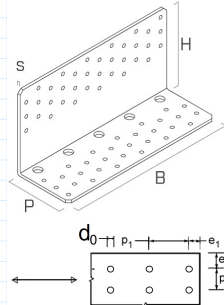
Angle of the load in relation to the grain direction

$$\alpha_{screw} := 90 \text{ deg}$$

Angle between screw axis and grain direction

$$t_x := 0 \text{ mm}$$

Xylofon thickness



EN 1993-1-8 Figure 3.1 & (1.5)(1)

Fastener

$$Type := 1.22$$

Screw

- 1.1 Diameter ($d \leq 6 \text{ mm}$)
 - 1.11 Predrilling
 - 1.12 No predrilling
- 1.2 Diameter ($d > 6 \text{ mm}$)
 - 1.21 Effective length covers ≥ 3 board layers
 - 1.22 Effective length covers < 3 board layers

Fastener geometry

$$d := 10 \text{ mm}$$

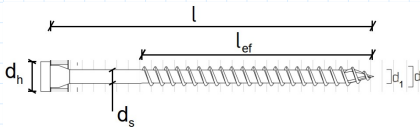
$$d_h := 16.5 \text{ mm}$$

$$d_1 := 6.6 \text{ mm}$$

$$d_s := 7.2 \text{ mm}$$

$$l := 70 \text{ mm}$$

$$l_{ef} := 56 \text{ mm}$$



Fastener material properties

$$F_{w,Rk} := 6.55 \text{ kN} \quad (\text{If needed})$$

$$F_{t,Rk} := 32 \text{ kN} \quad (\text{If needed})$$

$$f_{ub} := 1000 \text{ MPa}$$

EN 1993-1-8, Table 3.1

Bracket material properties

$$f_u := 430 \text{ MPa}$$

$$f_y := 275 \text{ MPa}$$

Bärande del 1, Table S2.1

CLT Material properties

$$\rho_k := 350 \frac{\text{kg}}{\text{m}^3}$$

(CLT handbook, Table 3.5)

Partial coefficients and strength modification factors

$$k_{mod} := 0.9$$

$$\gamma_M := 1.3 \quad \gamma_{M2} := 1.25 \quad \gamma_{M0} := 1.0$$

Below this nothing needs to be changed

Fastener types

$$Type_{screw} := (Type = 1.11) \vee (Type = 1.12) \vee (Type = 1.21) \vee (Type = 1.22)$$

Dimensions defined according to Eurocode or standards

If nothing else is mentioned, the equations comes from EN 1995-1-1:2004

$$t_{pen} := \min(l - S, l_{ef}) = 56 \text{ mm} \quad 8.3.2(4)$$

$$t_1 := l - S = 67.5 \text{ mm} \quad 8.2.3(3)$$

$$d_{ef} := \begin{cases} \text{if } (d_s = d) \wedge (l - l_{ef} \geq 4 \cdot d) \\ \quad \parallel d_s \\ \text{else} \\ \quad \parallel 1.1 \cdot d_1 \end{cases} = 7.26 \text{ mm} \quad 8.7.1(2)$$

10.6.1 Laterally loaded screws

- For smooth shank screws the following is valid:
- The rules in section 10.2, page 36, can be applied provided that an effective diameter d_e is used to account for the threaded part of the screw. d_e shall be used when determining the yield moment capacity and the embedment strength of the threaded part. d shall be used to determine spacing, end and edge distances and the effective number of screws.
 - For $d \leq 6 \text{ mm}$ the rules in section 10.4.1, page 40, och 10.4.2, page 41, can be applied.
 - For $d > 6 \text{ mm}$ the rules in section 10.5, page 44, can be applied.

$$t_p := S = 2.5 \text{ mm} \quad \text{EN 1993-1-8, (1.5)(1)}$$

$$t := S = 2.5 \text{ mm} \quad \text{EN 1993-1-8, Table 3.3 (3)}$$

$$A_v := (B - d_0 \cdot n) \cdot S = 258.75 \text{ mm}^2 \quad \text{Shear area of the steel plates cross section} \quad \text{CLT Handbook, (4.22)}$$

$$a_1 := p_1 = 39 \text{ mm}$$

$$A := \pi \cdot \frac{d_s^2}{4} = 40.715 \text{ mm}^2 \quad \text{Gross area of the screw}$$

Effective number of fasteners

$$n_{ef} := n = 5$$

CLT handbook (4.5.2)

When calculating the load-bearing capacity of the joint, Johansen's theory under Eurocode 5 should be used. For a joint with a group of wood screws, no reduction in the number of wood screws is required. The structure of the CLT panel prevents brittle fractures and splitting. However, this assumes that a minimum distance is maintained between the wood screws.

Embedment strength

$$f_1 := 10^6 \cdot \frac{\text{m}^2}{\text{s}^2} \quad f_2 := 10^6 \cdot \text{mm}^{0.3} \cdot \frac{\text{m}^2}{\text{s}^2} \quad f_3 := 10^6 \cdot \frac{\text{mm}^{0.3} \cdot \text{m}^{2.72}}{\text{kg}^{0.24} \cdot \text{s}^2} \quad \text{Unit correction}$$

CLT handbook ch. 4.5 states that nail and screw connections in general is designed according to Eurocode 5

$$f_{h,k} := \begin{cases} \text{if } Type = 1.11 \\ \quad \parallel 0.082 \cdot \left(1 - 0.01 \cdot \frac{d_{ef}}{\text{mm}} \right) \cdot \rho_k \cdot f_1 & 8.7.1(1) \text{ \& (5) \& (8.16)} \\ \text{else if } Type = 1.12 \\ \quad \parallel 0.082 \cdot \rho_k \cdot (d_{ef})^{-0.3} \cdot f_2 & 8.7.1(1) \text{ \& (5) \& (8.15)} \\ \text{else if } Type = 1.21 \\ \quad \parallel 0.019 \cdot \min(d_1, d_s)^{-0.3} \cdot \rho_k^{1.24} \cdot f_3 & (4.1) \text{ in CLT handbook} \\ \text{else if } Type = 1.22 \\ \quad \parallel \frac{0.082 \cdot \left(1 - 0.01 \cdot \frac{d_{ef}}{\text{mm}} \right) \cdot \rho_k}{\left(1.35 + 0.015 \cdot \frac{d_{ef}}{\text{mm}} \right) \cdot \left(\sin(\alpha_{load}) \right)^2 + \left(\cos(\alpha_{load}) \right)^2} \cdot f_1 & 8.7.1(1) \text{ \& (4) \& (8.31) - (8.33)} \\ \text{else} \\ \quad \parallel \text{return "Wrong fastener type"} \end{cases} = 18.24 \text{ MPa}$$

Yield moment of fastener

$$M_1 := \text{mm}^{0.4}$$

Unit correction

$$M_{y,Rk} := 0.3 \cdot f_{ub} \cdot (d_{ef})^{2.6} \cdot M_1 = 51.947 \text{ N} \cdot \text{m}$$

8.7.1(1) & (4)-(5) & (8.14) & (8-30)

Withdrawal capacity of fastener

$$F_1 := \frac{\text{m}^{2.4} \cdot \text{N}}{\text{mm}^{-0.6} \cdot \text{kg}^{0.8} \cdot \text{mm}^2}$$

Unit correction

$$F_{ax,Rk} := \begin{cases} \text{if } (Type = 1.11) \vee (Type = 1.12) \\ \quad \left| \begin{array}{l} \min(F_{w,Rk}, F_{t,Rk}) \\ \text{else if } (Type = 1.21) \vee (Type = 1.22) \\ \quad \text{if } (d \leq 12 \text{ mm}) \wedge \left(0.6 \leq \frac{d_1}{d} \leq 0.75\right) \\ \quad \left| \begin{array}{l} \min \left(\frac{(0.52 \cdot d^{-0.5} \cdot l_{ef}^{-0.1} \cdot \rho_k^{0.8}) \cdot d \cdot l_{ef} \cdot \min \left(\frac{d}{8 \text{ mm}}, 1 \right)}{1.2 \cdot (\cos(\alpha_{screw}))^2 + (\sin(\alpha_{screw}))^2} \right) \cdot F_1, F_{t,Rk} \right. \\ \text{else} \\ \quad \min(F_{w,Rk}, F_{t,Rk}) \end{array} \right. \\ \text{else} \\ \quad \text{return "Wrong fastener type"} \end{cases} = 6.68 \text{ kN}$$

DoTS vol.2, p.46, Failure mode 1 and 3

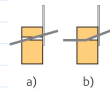
DoTS vol.2, p.46, Failure mode 1 and 3
8.7.2(4) & (8.38) - (8.40)

DoTS vol.2, p.46, Failure mode 1 and 3

Johansen's equations

Thin steel plate in single shear

$$F_{v,Rk,a} := 0.4 \cdot f_{hk} \cdot t_1 \cdot d = 4.93 \text{ kN}$$



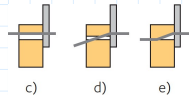
(8.9a)

$$F_{v,Rk,b} := 1.15 \cdot \sqrt{2 \cdot M_{y,Rk} \cdot f_{hk} \cdot d} = 5.01 \text{ kN}$$

(8.9b)

Thick steel plate in single shear

$$F_{v,Rk,c} := f_{hk} \cdot t_1 \cdot d = 12.31 \text{ kN}$$



(8.10c)

$$F_{v,Rk,d} := f_{hk} \cdot t_1 \cdot d \cdot \left(\sqrt{2 + \frac{4 \cdot M_{y,Rk}}{f_{hk} \cdot d \cdot t_1^2}} - 1 \right) = 6.16 \text{ kN}$$

(8.10d)

$$F_{v,Rk,e} := 2.3 \cdot \sqrt{M_{y,Rk} \cdot f_{hk} \cdot d} = 7.08 \text{ kN}$$

(8.10e)

Rope effect

$$k_T := \begin{cases} \text{if } Type_{screw} \\ \quad \left| \begin{array}{l} 1 \\ \text{else} \\ \quad \text{return "Wrong fastener type"} \end{array} \right. \end{cases} = 1$$

8.2.2(2)

Characteristic capacity per fastener

$$F_{v,Rk,EYM} := \begin{cases} \text{if } S \leq 0.5 \cdot d & \left[\min \left(F_{v,Rk,a}, F_{v,Rk,b} + \min \left(\frac{F_{ax,Rk}}{4}, F_{v,Rk,b} \cdot k_T \right) \right) \right] \\ \text{else if } S \geq d & \left[\min \left(F_{v,Rk,c}, F_{v,Rk,d} \cdot \downarrow, F_{v,Rk,e} \cdot \downarrow, \right. \right. \\ & \left. \left. + \min \left(\frac{F_{ax,Rk}}{4}, F_{v,Rk,d} \cdot k_T \right) + \min \left(\frac{F_{ax,Rk}}{4}, F_{v,Rk,e} \cdot k_T \right) \right) \right] \\ \text{else} & \left[\min \left(F_{v,Rk,a}, F_{v,Rk,b} + \min \left(\frac{F_{ax,Rk}}{4}, F_{v,Rk,b} \cdot k_T \right) \right) \cdot \downarrow \right. \\ & \left. - \min \left(F_{v,Rk,c}, F_{v,Rk,d} \cdot \downarrow, F_{v,Rk,e} \cdot \downarrow, \right. \right. \\ & \left. \left. + \min \left(\frac{F_{ax,Rk}}{4}, F_{v,Rk,d} \cdot k_T \right) + \min \left(\frac{F_{ax,Rk}}{4}, F_{v,Rk,e} \cdot k_T \right) \right) \right] \cdot (S - 0.5 \cdot d) \\ & \left. + \frac{\phantom{\min \left(F_{v,Rk,a}, F_{v,Rk,b} + \min \left(\frac{F_{ax,Rk}}{4}, F_{v,Rk,b} \cdot k_T \right) \right) \cdot \downarrow}}{0.5 \cdot d} \right] \end{cases} = 4.93 \text{ kN}$$

8.2.2(2) & 8.2.3(1)

Failure in the fastener

Shear failure

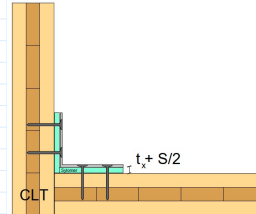
$$F_{v,Rk,f} := 0.6 \cdot f_{ub} \cdot A = 24.43 \text{ kN}$$

EN 1993-1-8 Table 3.4

Bending failure

Use Navier's with the screw acting as a cantilever beam

$$F_{b,Rk,g} := \frac{f_{ub} \cdot \pi \cdot \left(\frac{d_s}{2} \right)^3}{4 \cdot t_x + \frac{S}{2}} = 29.31 \text{ kN}$$



Failure in the bracket

Failure due to bearing pressure

$$\alpha_b := \min \left(\frac{e_1}{3 \cdot d_0}, \frac{p_1}{3 \cdot d_0} - \frac{1}{4}, \frac{f_{ub}}{f_u}, 1 \right) = 0.48$$

$$k_1 := \min \left(2.8 \cdot \frac{e_2}{d_0} - 1.7, 1.4 \cdot \frac{p_2}{d_0} - 1.7, 2.5 \right) = 2.3$$

EN 1993-1-8 Table 3.4

$$F_{v,Rk,h} := k_1 \cdot \alpha_b \cdot f_u \cdot d \cdot t = 11.77 \text{ kN}$$

Shear failure

$$V_{c,Rk,i} := \frac{A_v \cdot f_y}{\sqrt{3}} = 41.08 \text{ kN}$$

CLT handbook, (4.22)

Characteristic capacity in the connection

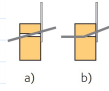
$$F_{Rk} := \min (F_{v,Rk,EYM} \cdot n_{ef} \cdot n_{rows}, F_{v,Rk,f} \cdot n_{ef} \cdot n_{rows}, F_{v,Rk,h} \cdot n_{ef} \cdot n_{rows}, V_{c,Rk,i}, F_{b,Rk,g} \cdot n_{ef} \cdot n_{rows}) = 41.08 \text{ kN}$$

Design capacities

Johansen's equations

Thin steel plate in single shear

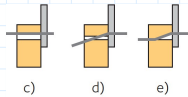
$$F_{v,Rd,a} := F_{v,Rk,a} \cdot \frac{k_{mod}}{\gamma_M} = 3.41 \text{ kN} \quad (2.17)$$



$$F_{v,Rd,b} := \left(F_{v,Rk,b} + \min \left(\frac{F_{ax,Rk}}{4}, F_{v,Rk,b} \cdot k_T \right) \right) \cdot \frac{k_{mod}}{\gamma_M} = 4.62 \text{ kN} \quad (2.17)$$

Thick steel plate in single shear

$$F_{v,Rd,c} := F_{v,Rk,c} \cdot \frac{k_{mod}}{\gamma_M} = 8.53 \text{ kN} \quad (2.17)$$



$$F_{v,Rd,d} := \left(F_{v,Rk,d} + \min \left(\frac{F_{ax,Rk}}{4}, F_{v,Rk,d} \cdot k_T \right) \right) \cdot \frac{k_{mod}}{\gamma_M} = 5.42 \text{ kN} \quad (2.17)$$

$$F_{v,Rd,e} := \left(F_{v,Rk,e} + \min \left(\frac{F_{ax,Rk}}{4}, F_{v,Rk,e} \cdot k_T \right) \right) \cdot \frac{k_{mod}}{\gamma_M} = 6.06 \text{ kN} \quad (2.17)$$

Design capacity per fastener

$$F_{v,Rd,EYM} := F_{v,Rk,EYM} \cdot \frac{k_{mod}}{\gamma_M} = 3.41 \text{ kN} \quad (2.17)$$

Failure in the fastener

Shear failure

$$F_{v,Rd,f} := \frac{F_{v,Rk,f}}{\gamma_{M2}} = 19.54 \text{ kN} \quad \text{EN 1993-1-8 Table 3.4}$$

Bending failure

$$F_{b,Rd,g} := \frac{F_{b,Rk,g}}{\gamma_{M2}} = 23.45 \text{ kN}$$

Failure in the bracket

Failure due to bearing pressure

$$F_{v,Rd,h} := \frac{F_{v,Rk,h}}{\gamma_{M2}} = 9.42 \text{ kN} \quad \text{EN 1993-1-8 Table 3.4}$$

Shear failure

$$V_{c,Rd,i} := \frac{V_{c,Rk,i}}{\gamma_{M0}} = 41.08 \text{ kN} \quad \text{CLT handbook, (4.22)}$$

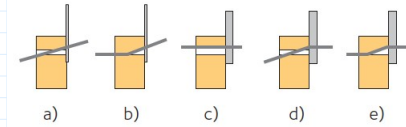
Design capacity in the connection

$$F_{Rd} := \min(F_{v.Rd.EYM} \cdot n_{ef} \cdot n_{rows}, F_{v.Rd.f} \cdot n_{ef} \cdot n_{rows}, F_{v.Rd.h} \cdot n_{ef} \cdot n_{rows}, V_{c.Rd.i}, F_{b.Rd.g} \cdot n_{ef} \cdot n_{rows}) = 34.1 \text{ kN}$$

Failure mode

```

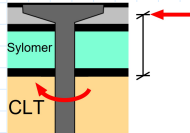
Failure_mode_d := if F_{v.Rd.a} \cdot n_{ef} \cdot n_{rows} = F_{Rd}           = "a"
                  || return "a"
                  else if F_{v.Rd.b} \cdot n_{ef} \cdot n_{rows} = F_{Rd}
                  || return "b"
                  else if F_{v.Rd.c} \cdot n_{ef} \cdot n_{rows} = F_{Rd}
                  || return "c"
                  else if F_{v.Rd.d} \cdot n_{ef} \cdot n_{rows} = F_{Rd}
                  || return "d"
                  else if F_{v.Rd.e} \cdot n_{ef} \cdot n_{rows} = F_{Rd}
                  || return "e"
                  else if F_{v.Rd.f} \cdot n_{ef} \cdot n_{rows} = F_{Rd}
                  || return "f"
                  else if F_{v.Rd.h} \cdot n_{ef} \cdot n_{rows} = F_{Rd}
                  || return "h"
                  else if V_{c.Rd.i} = F_{Rd}
                  || return "i"
                  else if F_{b.Rd.g} \cdot n_{ef} \cdot n_{rows} = F_{Rd}
                  || return "g"
                  else if F_{v.Rd.EYM} \cdot n_{ef} \cdot n_{rows} = F_{Rd}
                  || return "Mixed failure of a-e"
                  else
                  || return "Something wrong"
    
```



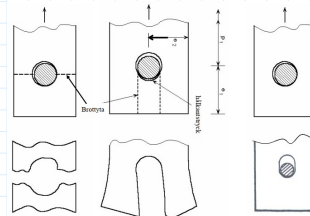
f = shear failure of the fastener



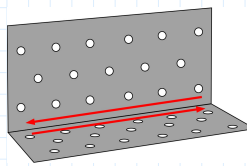
g = bending failure of the fastener



h = failure modes in the bracket due to bearing pressure



i = shear failure of the bracket



F MATLAB - Parametric Study

2025-05-19 11:00 C:\Users\alex... 1 of 18

```
clear all; clc; close all;

% Inputs
l = 180; % Vary between 60, 70, 80 and 90 [mm]
lef_limit = 120; %60 for wall (100CLT), 120 for floor✓
(200CLT) [mm] !! HAVE TO BE CHANGED IF SWITCHING BETWEEN✓
WALL AND FLOOR ELEMENT !!
tx = 6; % mm (Xylomer thickness)
t_bracket = [0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5]; %✓
Bracket thickness
alpha_load = pi/2; % Load direction relative grain
alpha_screw = pi/2; % Screw direction relative grain
Load = 48.9*1.5; % Design load
N_brackets = 4; % # of brackets
k_T = 1; % Rope effect for screw
gamma_Rd = 1.0; % Overstrength factor

% Fastener material properties
Ft_Rk = 32; % kN
fub = 800; % MPa

% Bracket material properties
fu = 360; % MPa
fy = 235; % MPa

% CLT material properties
rho_k = 350; % kg/m^3

% Partial coefficients and strength modification factors
kmod = 0.9;
gamma_M = 1.3;
gamma_M0 = 1.0;
gamma_M2 = 1.25;

% Creating a matrix of screw geometry, inter- and✓
extrapolating the
% intermediate diameters (d increase with constant✓
```

```
increment).
screws_input = [8 10 12];
screws_values = [13.5 16.5 18.5;
                 5.9 6.6 7.3;
                 6.3 7.2 8.55;
                 11 13 14
                 ];
x_value= [5 6 7 9 11 13 14];

for i = 1:length(screws_values)
    y_value(i,:) = interp1(screws_input,screws_values(i,:),x_value,'linear','extrap');
end
screws_unknown = [x_value; y_value]';
screws_known = [screws_input' screws_values'];
screws = sort([screws_unknown; screws_known]);
N_screws = zeros(size(screws,1),length(t_bracket));
N_screws(:, :) = 1;

% Looping through screws and adding effective length (lef)
and
% lateral withdrawal capacity (F_W)
for i = 1:length(screws)
    % l = 60
    if l == 60
        lef = 52;
        if screws(i,1) == 5
            F_w = 2.10;
        elseif screws(i,1) == 6
            F_w = 2.90;
        elseif screws(i,1) == 7
            F_w = 3.69;
        elseif screws(i,1) == 8
            F_w = 4.49;
        elseif screws(i,1) == 9
            F_w = 5.29;
        elseif screws(i,1) == 10
```

```
        F_w = 6.08;
elseif screws(i,1) == 11
        F_w = 6.69;
elseif screws(i,1) == 12
        F_w = 7.29;
elseif screws(i,1) == 13
        F_w = 7.9;
elseif screws(i,1) == 14
        F_w = 8.51;
end
% l = 70
elseif l == 70 && screws(i,1) < 9
    lef = 53.5;
    if screws(i,1) == 5
        F_w = 2.25;
    elseif screws(i,1) == 6
        F_w = 3.06;
    elseif screws(i,1) == 7
        F_w = 3.87;
    elseif screws(i,1) == 8
        F_w = 4.82;
    end

elseif l == 70 && screws(i,1) == 9
    lef = 54.75;
    F_w = 5.62;

elseif l == 70 && screws(i,1) > 9
    lef = 56;
    if screws(i,1) == 10
        F_w = 6.55;
    elseif screws(i,1) == 11
        F_w = 7.2;
    elseif screws(i,1) == 12
        F_w = 7.86;
    elseif screws(i,1) == 13
        F_w = 8.51;
```

```
        elseif screws(i,1) == 14
            F_w = 9.16;
        end
% l = 80
    elseif l == 80 && screws(i,1) < 9
        lef = 55;
        if screws(i,1) == 5
            F_w = 2.39;
        elseif screws(i,1) == 6
            F_w = 3.22;
        elseif screws(i,1) == 7
            F_w = 4.04;
        elseif screws(i,1) == 8
            F_w = 5.15;
        end

    elseif l == 80 && screws(i,1) == 9
        lef = 57.5;
        F_w = 5.94;

    elseif l == 80 && screws(i,1) > 9
        lef = 60;
        if screws(i,1) == 10
            F_w = 7.02;
        elseif screws(i,1) == 11
            F_w = 7.72;
        elseif screws(i,1) == 12
            F_w = 8.42;
        elseif screws(i,1) == 13
            F_w = 9.12;
        elseif screws(i,1) == 14
            F_w = 9.82;
        end

% l = 90
    elseif l == 90 && screws(i,1) < 9
        lef = 65;
```

```
    if screws(i,1) == 5
        F_w = 3.36;
    elseif screws(i,1) == 6
        F_w = 4.27;
    elseif screws(i,1) == 7
        F_w = 5.18;
    elseif screws(i,1) == 8
        F_w = 6.09;
    end

elseif l == 90 && screws(i,1) == 9
    lef = 66.25;
    F_w = 6.99;

elseif l == 90 && screws(i,1) > 9
    lef = 67.5;
    if screws(i,1) == 10
        F_w = 7.9;
    elseif screws(i,1) == 11
        F_w = 8.69;
    elseif screws(i,1) == 12
        F_w = 9.48;
    elseif screws(i,1) == 13
        F_w = 10.26;
    elseif screws(i,1) == 14
        F_w = 11.05;
    end

% l = 100
elseif l == 100
    lef = 75;
    if screws(i,1) == 5
        F_w = 4.38;
    elseif screws(i,1) == 6
        F_w = 5.26;
    elseif screws(i,1) == 7
        F_w = 6.14;
```

```
elseif screws(i,1) == 8
    F_w = 7.02;
elseif screws(i,1) == 9
    F_w = 7.90;
elseif screws(i,1) == 10
    F_w = 8.78;
elseif screws(i,1) == 11
    F_w = 9.66;
elseif screws(i,1) == 12
    F_w = 10.53;
elseif screws(i,1) == 13
    F_w = 11.41;
elseif screws(i,1) == 14
    F_w = 12.28;
end

% l = 140
elseif l == 140
    lef = 110;
    if screws(i,1) == 5
        F_w = 6.45;
    elseif screws(i,1) == 6
        F_w = 7.73;
    elseif screws(i,1) == 7
        F_w = 9.02;
    elseif screws(i,1) == 8
        F_w = 10.3;
    elseif screws(i,1) == 9
        F_w = 11.59;
    elseif screws(i,1) == 10
        F_w = 12.87;
    elseif screws(i,1) == 11
        F_w = 14.16;
    elseif screws(i,1) == 12
        F_w = 15.44;
    elseif screws(i,1) == 13
        F_w = 16.73;
```

```
        elseif screws(i,1) == 14
            F_w = 18.01;
        end

% l = 180
elseif l == 180 && screws(i,1) < 12
    lef = 150;
    if screws(i,1) == 5
        F_w = 8.8;
    elseif screws(i,1) == 6
        F_w = 10.55;
    elseif screws(i,1) == 7
        F_w = 12.3;
    elseif screws(i,1) == 8
        F_w = 14.05;
    elseif screws(i,1) == 9
        F_w = 15.8;
    elseif screws(i,1) == 10
        F_w = 17.55;
    elseif screws(i,1) == 11
        F_w = 18.61;
    end

elseif l == 180 && screws(i,1) >= 12
    lef = 140;
    if screws(i,1) == 12
        F_w = 19.66;
    elseif screws(i,1) == 13
        F_w = 21.29;
    elseif screws(i,1) == 14
        F_w = 22.92;
    end

end

screws(i,6) = lef;
screws(i,7) = F_w;
end
```

```
screws
%
% Looping through all bracket thicknesses
for i = 1:length(t_bracket)

    S = t_bracket(i);

    % Looping through all screws
    for j = 1:length(screws)

        % Fastener geometry and properties
        d = screws(j,1); % Diameter
        dh = screws(j,2); % Head diameter
        d1 = screws(j,3); % Inner thread diameter
        ds = screws(j,4); % Shank diameter
        d0 = screws(j,5); % Hole diameter
        lef = screws(j,6); % Effective length
        F_withdrawal_Rk = screws(j,7); % Withdrawal ✓
    end
end

capacity
t1 = 1 - S; % Penetration of entire screw in timber
A = pi * (ds^2) / 4; % Gross area of screw

% Bracket geometry
p1 = 2.2*d0; % mm (Tabel 3.3 in EN1993-1-8)
p2 = 2.4*d0; % mm (Tabel 3.3 in EN1993-1-8)
e1 = 1.2*d0; % mm (Tabel 3.3 in EN1993-1-8)
e2 = 1.2*d0; % mm (Tabel 3.3 in EN1993-1-8)

% Determining effective diameter
if (ds == d) && (1-lef >= 4*d)
    d_ef = ds;
else
    d_ef = 1.1*d1;
end

% Determining screw type
if d <= 6
```

```

        Type = '1.12';
elseif lef < lef_limit
        Type = '1.22';
else
        Type = '1.21';
end

% Embedment Strength (MPa), depending on screw
type.
if Type == '1.11'
        fh_k = 0.082*(1-0.01*d_ef)*rho_k
elseif Type == '1.12'
        fh_k = 0.082 * rho_k * d_ef^(-0.3);
elseif Type == '1.21'
        fh_k = 0.019 * min(d1, ds)^(-0.3) * rho_k^1.24;
elseif Type == '1.22'
        fh_k = 0.082*(1-0.01*d_ef)*rho_k / ((1.35+0.
015*d_ef)*(sin(alpha_load)^2+(cos(alpha_load))^2));
else
        error('Wrong fastener type');
end

% Yield Moment of Fastener (N·mm).
My_Rk = 0.3 * fub * d_ef^2.6/1000;

% Withdrawal Capacity (kN), depending on screw
type.
if any(strcmp(Type, {'1.11', '1.12'}))
        Fax_Rk = min(F_withdrawal_Rk, Ft_Rk);
elseif any(strcmp(Type, {'1.21', '1.22'}))
        if (d <= 12) && (0.6 <= d1/d) && (d1/d <= 0.75)
                Fax_Rk = min(0.52*d^(-0.5)*lef^(-0.1)
*rho_k^(0.8) * d * lef * min(d/8, 1) / (1.2*(cos
(alpha_screw))^2 + (sin(alpha_screw))^2)/1000, Ft_Rk);
        else
                Fax_Rk = min(F_withdrawal_Rk, Ft_Rk);
        end
end

```

```

else
    error('Wrong fastener type');
end

% Johansen's equations for lateral resistance (kN)
Fv_Rk_a = 0.4 * fh_k * t1 * d / 1000;
Fv_Rk_b = 1.15 * sqrt(2 * My_Rk * fh_k*10^6 *
d/1000) / 1000;
Fv_Rk_c = fh_k * t1 * d / 1000 ;
Fv_Rk_d = fh_k*10^6 * t1/1000 * d/1000 * (sqrt(2 +
4 * My_Rk / (fh_k*10^6 * d/1000 * (t1/1000)^2)) - 1) /
1000;
Fv_Rk_e = 2.3 * sqrt(My_Rk * fh_k*10^6 * d/1000) /
1000;

% Characteristic capacity per fastener [kN],
determined by
% thickness of plate and diameter
if S <= 0.5 * d
    Fv_Rk_EYM = min([Fv_Rk_a, Fv_Rk_b + min
(Fax_Rk/4, Fv_Rk_b*k_T)]);
    if Fv_Rk_EYM == Fv_Rk_a
        Fv_Rk_EYM_index(j,i) = 'a';
    else
        Fv_Rk_EYM_index(j,i) = 'b';
    end
elseif S >= d
    Fv_Rk_EYM = min([Fv_Rk_c, Fv_Rk_d + min
(Fax_Rk/4, Fv_Rk_d*k_T), Fv_Rk_e + min(Fax_Rk/4,
Fv_Rk_e*k_T)]);
    if Fv_Rk_EYM == Fv_Rk_c
        Fv_Rk_EYM_index(j,i) = 'c';
    elseif Fv_Rk_EYM == Fv_Rk_d + min(Fax_Rk/4,
Fv_Rk_d*k_T)
        Fv_Rk_EYM_index(j,i) = 'd';
    else
        Fv_Rk_EYM_index(j,i) = 'e';

```

```

        end
    else
        Fv_Rk_EYM = min([Fv_Rk_a, Fv_Rk_b + min(
Fax_Rk/4, Fv_Rk_b*k_T)]) + abs(min([Fv_Rk_a, Fv_Rk_b + min(
Fax_Rk/4, Fv_Rk_b*k_T)]) - min([Fv_Rk_c, Fv_Rk_d + min(
Fax_Rk/4, Fv_Rk_d*k_T), Fv_Rk_e + min(Fax_Rk/4,
Fv_Rk_e*k_T)])) * (S-0.5*d)/(0.5*d);
        Fv_Rk_EYM_index(j,i) = 'm';
    end

    % Shear failure of fastener [kN]
    Fv_Rk_f = 0.6 * fub * A * 1/1000;

    % Bending failure of fastener [kN]
    Fb_Rk_g = (fub * pi * ((ds/2)^3/4)) / (tx + S/2) *
(1/1000);

    % Bearing failure in bracket [kN]
    alpha_b = min([e1/(3*d0), p1/(3*d0), 1, fub/fu]);
    k1 = min([2.8 * e2/d0 - 1.7, 1.4 * p2/d0, 2.5]);
    Fv_Rk_h = k1 * alpha_b * fu * d * S * (1/1000);

    % Design capacities
    Fv_Rd_EYM = Fv_Rk_EYM * kmod / gamma_M;
    Fv_Rd_f = Fv_Rk_f / gamma_M2;
    Fb_Rd_g = Fb_Rk_g / gamma_M2;
    Fv_Rd_h = Fv_Rk_h / gamma_M2 ;

    % List of design capacities for single fastener
    Fv_Rd_single = [Fv_Rd_EYM;
                    Fv_Rd_f;
                    Fb_Rd_g;
                    Fv_Rd_h;
                    ];

    % All failuremodes and capacities for all
combinations of screws

```

```

    % and plate thicknesses
    % (Output matrix: diameter of screw x plate
thickness x failuremode in Fv_Rd)
    for k = 1:length(Fv_Rd_single)
        Fd_single_all_failuremodes(j,i,k) =
Fv_Rd_single(k);
    end

    % Taking the minimum value of all failure modes for
a single fastener
    [Fd_min_single(j,i), Fd_single_min_failuremode(j,
i)] = min(Fv_Rd_single);

    % Marking which failure mode is governing for each
combination of
    % diameter and plate thickness (For a single
fastener)
    if min(Fv_Rd_single) == Fv_Rd_single(1)
        Fd_min_single_index(j,i) = Fv_Rk_EYM_index(j,
i);
    elseif min(Fv_Rd_single) == Fv_Rd_single(2)
        Fd_min_single_index(j,i) = 'f';
    elseif min(Fv_Rd_single) == Fv_Rd_single(3)
        Fd_min_single_index(j,i) = 'g';
    elseif min(Fv_Rd_single) == Fv_Rd_single(4);
        Fd_min_single_index(j,i) = 'h';
    end

    % Design bracket according to shear failure and
checking if all
    % failure modes can achieve design load.

    while true
        % Shear failure in bracket [kN]
        B = 2*e1 + (ceil(N_screws(j,i)/2)-1)*p1; %

```

```

Width of bracket
    Av = (B - d0*ceil(N_screws(j,i)/2)) * S; %✓
Shear area of bracket
    Vc_Rk_i = Av * fy / sqrt(3) * (1/1000);
    Vc_Rd_i = Vc_Rk_i / gamma_M0 ; % Design shear✓
capacity of bracket

    Fv_Rd = [
        Fv_Rd_EYM*N_screws(j,i)/gamma_Rd;
        Fv_Rd_f*N_screws(j,i)/gamma_Rd;
        Fb_Rd_g*N_screws(j,i)/gamma_Rd;
        Fv_Rd_h*N_screws(j,i);
        Vc_Rd_i
    ];

    % Checking if minimum capacity is enough for✓
design load,
    % adding 1 screw if not enough.
    Fv_Rd_min(j,i) = min(Fv_Rd);
    if Fv_Rd_min(j,i) >= Load/4
        break;
    end

    N_screws(j,i) = N_screws(j,i) + 1;
    if N_screws(j,i) > 100
        warning('Too many screws');
        break;
    end
end
    B_all(j,i) = B; % Saving the width of the bracket✓
for the given bracket thickness and screw diameter.

    % All failuremodes and capacities for all✓
connection combinations
    % (Output matrix: diameter of screw x plate✓
thickness x failuremode in Fv_Rd)
    for k = 1:length(Fv_Rd)

```

```
Fd_all_failuremodes(j,i,k) = Fv_Rd(k);
end

% Marking which failure mode is governing for each
combination of
% diameter and plate thickness (For a entire
connection)
if min(Fv_Rd) == Fv_Rd(1)
    Fd_min_index(j,i) = Fv_Rk_EYM_index(j,i);
elseif min(Fv_Rd) == Fv_Rd(2)
    Fd_min_index(j,i) = 'f';
elseif min(Fv_Rd) == Fv_Rd(3)
    Fd_min_index(j,i) = 'g';
elseif min(Fv_Rd) == Fv_Rd(4)
    Fd_min_index(j,i) = 'h';
else
    Fd_min_index(j,i) = 'i';
end
end
end

% Displaying results
disp('Capacity of an entire bracket')
diameters = screws(:,1);
thicknessNames = strcat('t=', replace(string(t_bracket),
'.' , '.'));
N_table = array2table(Fv_Rd_min, 'VariableNames',
thicknessNames);
N_table.Properties.RowNames = strcat('d=', replace(string
(diameters), '.' , '.'));
disp(N_table);

disp('Governing failure mode')
N_table = array2table(Fd_min_index, 'VariableNames',
thicknessNames);
N_table.Properties.RowNames = strcat('d=', replace(string
(diameters), '.' , '.'));
```

```
disp(N_table);

disp('# of screws needed to achieve needed design
capacity')
N_table = array2table(N_screws, 'VariableNames',
thicknessNames);
N_table.Properties.RowNames = strcat('d=', replace(string
(diameters), '.', '.'));
disp(N_table);

disp('Width of bracket')
N_table = array2table(B_all, 'VariableNames',
thicknessNames);
N_table.Properties.RowNames = strcat('d=', replace(string
(diameters), '.', '.'));
disp(N_table);

disp('Capacity of single fastener')
N_table = array2table(Fd_min_single, 'VariableNames',
thicknessNames);
N_table.Properties.RowNames = strcat('d=', replace(string
(diameters), '.', '.'));
disp(N_table);

%PLOTS

% Plotting # of screws against t_bracket
y = N_screws(2:2:end,:);
x = t_bracket;

figure;
hold on;
grid on;
colors = lines(size(y,1));

% Plot each curve
```

```
for i = 1:size(y,1)
    plot(x, y(i,:), '-o','Linewidth', 1.5, 'Color', colors(
(i,:), 'DisplayName', ['d = ' num2str(screws(i*2,1)) '
mm']));
    % Adding failure mode to each point
    for j = 1:length(x)
        text(x(j),y(i,j), [' ' Fd_min_index(i,j)], ...
            'VerticalAlignment', 'bottom', ...
            'HorizontalAlignment', 'left', ...
            'FontSize', 14, ...
            'Color', colors(i,:));
    end
end
xlabel('Bracket thickness [mm]','FontSize', 14);
ylabel('Number of fasteners needed to achieve
capacity','FontSize', 14);
title(['L = ' num2str(l) ' mm'],'FontSize', 16);
legend show;
set(legend, 'FontSize',14)

matlab2tikz(['L' num2str(l) '_n.tex'])

% Plotting Width of bracket against t_bracket
x = t_bracket;
y = B_all(2:2:end,:);

figure;
hold on;
grid on;
colors = lines(size(y,1));

% Plot each curve
for i = 1:size(y,1)
    plot(x, y(i,:), '-o','Linewidth', 1.5, 'Color', colors(
(i,:), 'DisplayName', ['d = ' num2str(screws(i*2,1)) '
mm']));
```

```
% Adding failure mode to each point
for j = 1:length(x)
    text(x(j), y(i,j), [' ' Fd_min_index(i,j)], ...
        'VerticalAlignment', 'bottom', ...
        'HorizontalAlignment', 'left', ...
        'FontSize', 14, ...
        'Color', colors(i,:));
end
end
xlabel('Bracket thickness [mm]', 'FontSize', 14);
ylabel('Width of bracket [mm]', 'FontSize', 14);
title(['L = ' num2str(l) ' mm'], 'FontSize', 16);
legend show;
set(legend, 'FontSize', 14)

matlab2tikz(['L' num2str(l) '_B.tex'])

% Plotting single fastener capacity against bracket ✓
thickness
y = Fd_min_single(2:2:end, :);
x = t_bracket;
Index = Fd_min_single_index;

figure;
hold on;
grid on;
colors = lines(size(y,1));

% Plot each curve
for i = 1:size(y,1)
    plot(x, y(i,:), '-o', 'Linewidth', 1.5, 'Color', colors ✓
        (i,:), 'DisplayName', ['d = ' num2str(screws(i*2,1)) ' ✓
        mm']);

    % Adding failure mode to each point
```

```
for j = 1:length(x)
    text(x(j),y(i,j), [' ' Index(i,j)], ...
        'VerticalAlignment', 'bottom', ...
        'HorizontalAlignment', 'left', ...
        'FontSize', 14, ...
        'Color', colors(i,:));
end
end
xlabel('Bracket thickness [mm]', 'FontSize', 14);
ylabel('Capacity [kN]', 'FontSize', 14);
title(['L = ' num2str(l) ' mm'], 'FontSize', 16);
legend show;
set(legend, 'FontSize',14)

matlab2tikz(['L' num2str(l) '_F.tex'])
```

G Screw input data

Interpolation/Extrapolation of following values:

- Screwhead diameter (dh)
- Inner thread diameter (d1)
- Shank diameter (ds)
- plate hole diameter (d0)
- Thread length (lef)
- Rax_90_k (F_w)

Assumptions:

Dimensions regarding the diameter are interpolated/extrapolated between the given values for 8, 10 and 12 mm. The given values for lef and F_w are inserted into the specified diameters (marked in green), and the remaining values within the diameter are interpolated/extrapolated (both lef and F_w). Then the remaining values for all diameters and lengths are interpolated/extrapolated.

d [mm]	dh [mm]	d1 [mm]	ds [mm]	d0 [mm]	L [mm]	lef [mm]	F_w [kN]
5	9	4.85	4.95	8	60	52	2.10
					70	53.5	2.25
					80	55	2.39
					90	65	3.36
					100	75	4.38
					140	110	6.45
					180	150	8.80
6	10.5	5.2	5.4	9	60	52	2.90
					70	53.5	3.06
					80	55	3.22
					90	65	4.27
					100	75	5.26
					140	110	7.73
					180	150	10.55
7	12	5.55	5.85	10	60	52	3.69
					70	53.5	3.87
					80	55	4.04
					90	65	5.18
					100	75	6.14
					140	110	9.02
					180	150	12.30

d [mm]	dh [mm]	d1 [mm]	ds [mm]	d0 [mm]	L [mm]	lef [mm]	F_w [kN]
8	13.5	5.9	6.3	11	60	52	4.49
					70	53.5	4.82
					80	55	5.15
					90	65	6.09
					100	75	7.02
					140	110	10.30
					180	150	14.05
9	15	6.25	6.75	12	60	52	5.29
					70	54.75	5.62
					80	57.5	5.94
					90	66.25	6.99
					100	75	7.90
					140	110	11.59
					180	150	15.80
10	16.5	6.6	7.2	13	60	52	6.08
					70	56	6.55
					80	60	7.02
					90	67.5	7.90
					100	75	8.78
					140	110	12.87
					180	150	17.55
11	17.5	6.95	7.875	13.5	60	52	6.69
					70	56	7.20
					80	60	7.72
					90	67.5	8.69
					100	75	9.66
					140	110	14.16
					180	150	18.61
12	18.5	7.3	8.55	14	60	52	7.29
					70	56	7.86
					80	60	8.42
					90	67.5	9.48
					100	75	10.53
					120	90	12.64
					140	110	15.44
180	140	19.66					

d [mm]	dh [mm]	d1 [mm]	ds [mm]	d0 [mm]	L [mm]	lef [mm]	F_w [kN]
13	19.5	7.65	9.225	14.5	60	52	7.90
					70	56	8.51
					80	60	9.12
					90	67.5	10.26
					100	75	11.41
					140	110	16.73
					180	140	21.29
14	20.5	8	9.9	15	60	52	8.51
					70	56	9.16
					80	60	9.82
					90	67.5	11.05
					100	75	12.28
					140	110	18.01
					180	140	22.92

H Results from parametric study

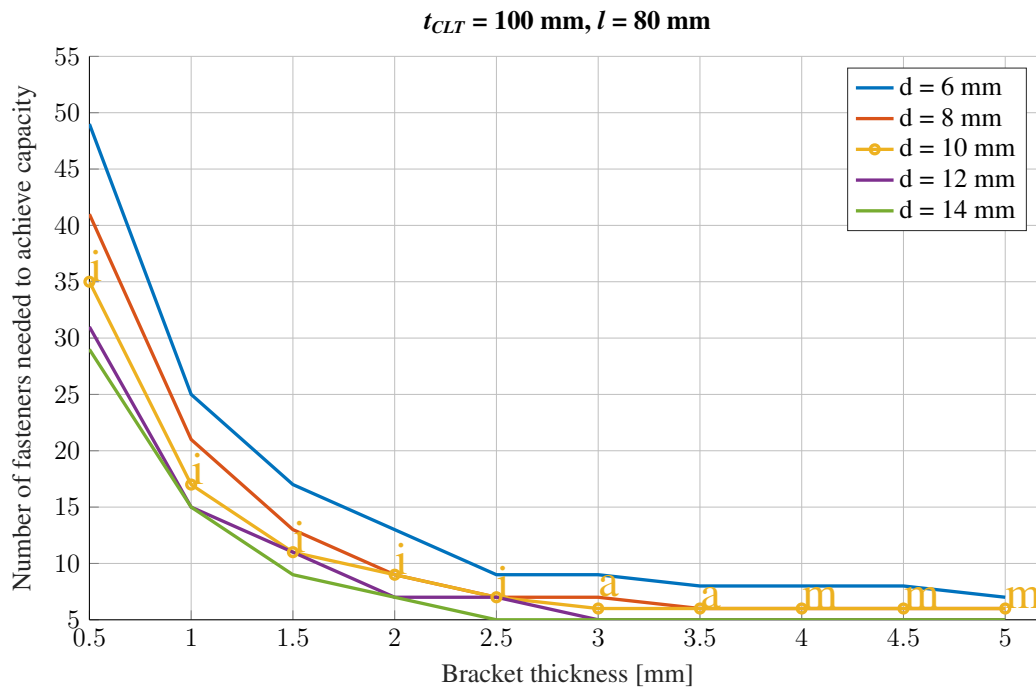


Figure H.1: Required number of 80 mm long fasteners to carry the design load from the case study, shown for various fastener diameters and plate thicknesses, with a CLT thickness of 100 mm. For readability, governing failure modes are indicated only for the 10 mm diameter screw. See Table 4.2 for a description of the failure modes.

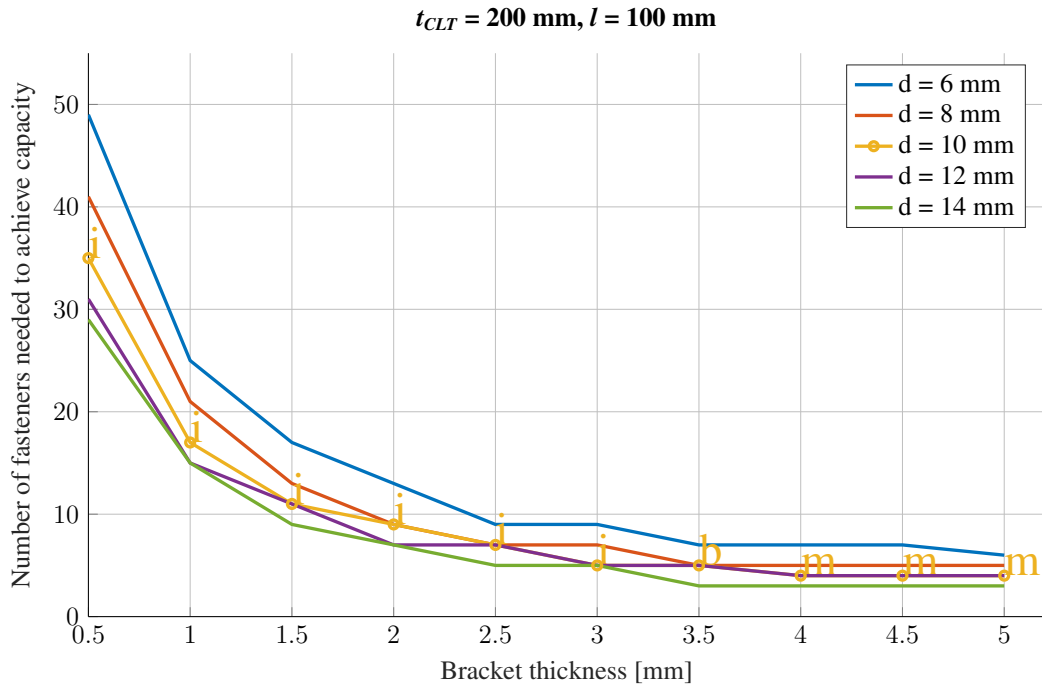


Figure H.2: Required number of 100 mm long fasteners to carry the design load from the case study, shown for various fastener diameters and plate thicknesses, with a CLT thickness of 200 mm. For readability, governing failure modes are indicated only for the 10 mm diameter screw. See Table 4.2 for a description of the failure modes.

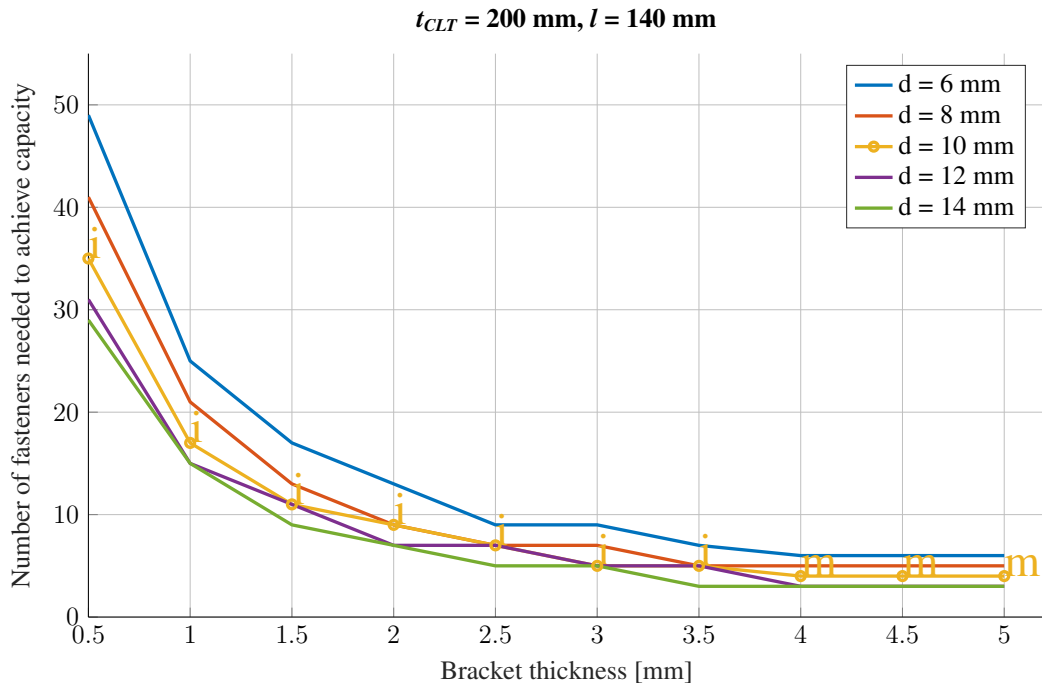


Figure H.3: Required number of 140 mm long fasteners to carry the design load from the case study, shown for various fastener diameters and plate thicknesses, with a CLT thickness of 200 mm. For readability, governing failure modes are indicated only for the 10 mm diameter screw. See Table 4.2 for a description of the failure modes.

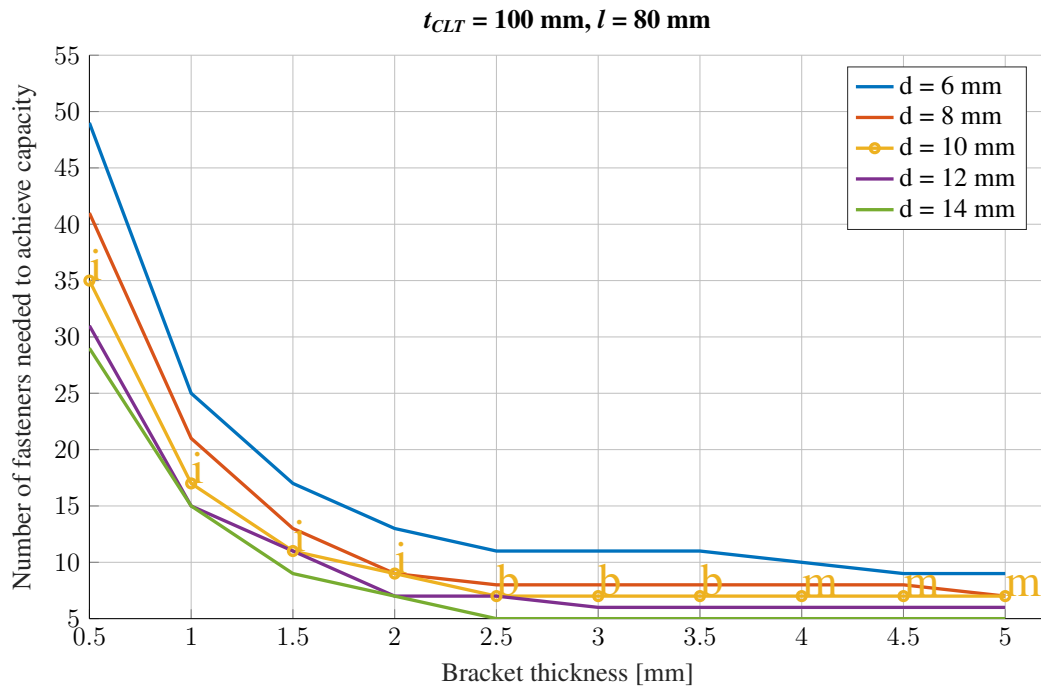


Figure H.4: Required number of 80 mm long fasteners to carry the design load from the case study, with the rope effect excluded, shown for various fastener diameters and plate thicknesses, with a CLT thickness of 100 mm. For readability, governing failure modes are indicated only for the 10 mm diameter screw. See Table 4.2 for a description of the failure modes.

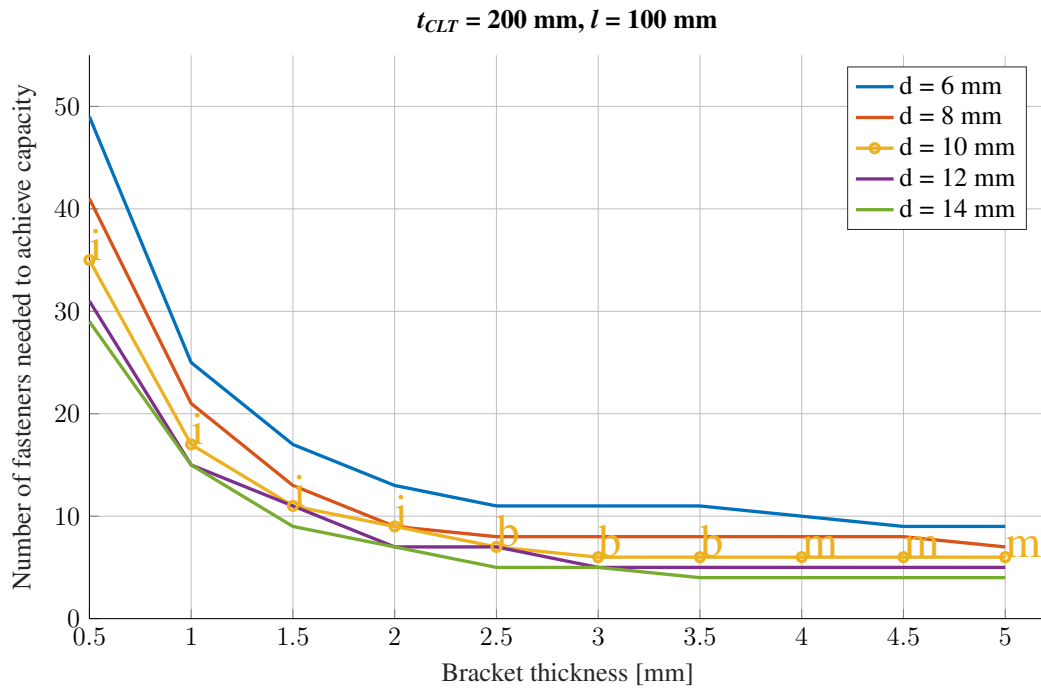


Figure H.5: Required number of 100 mm long fasteners to carry the design load from the case study, with the rope effect excluded, shown for various fastener diameters and plate thicknesses, with a CLT thickness of 200 mm. For readability, governing failure modes are indicated only for the 10 mm diameter screw. See Table 4.2 for a description of the failure modes.

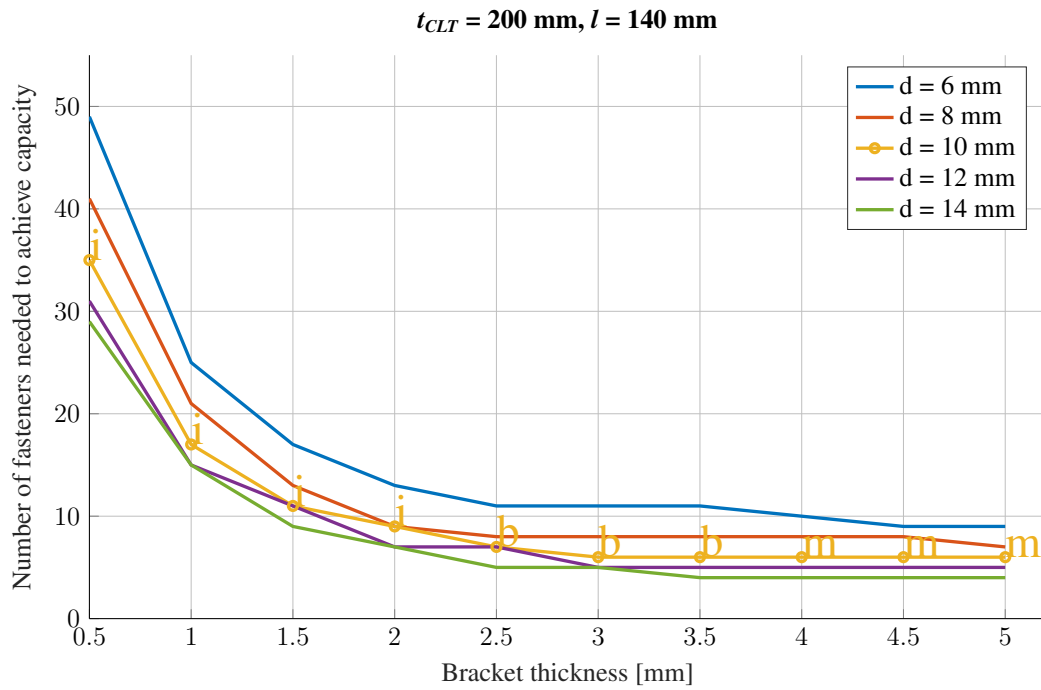


Figure H.6: Required number of 140 mm long fasteners to carry the design load from the case study, with the rope effect excluded, shown for various fastener diameters and plate thicknesses, with a CLT thickness of 200 mm. For readability, governing failure modes are indicated only for the 10 mm diameter screw. See Table 4.2 for a description of the failure modes.

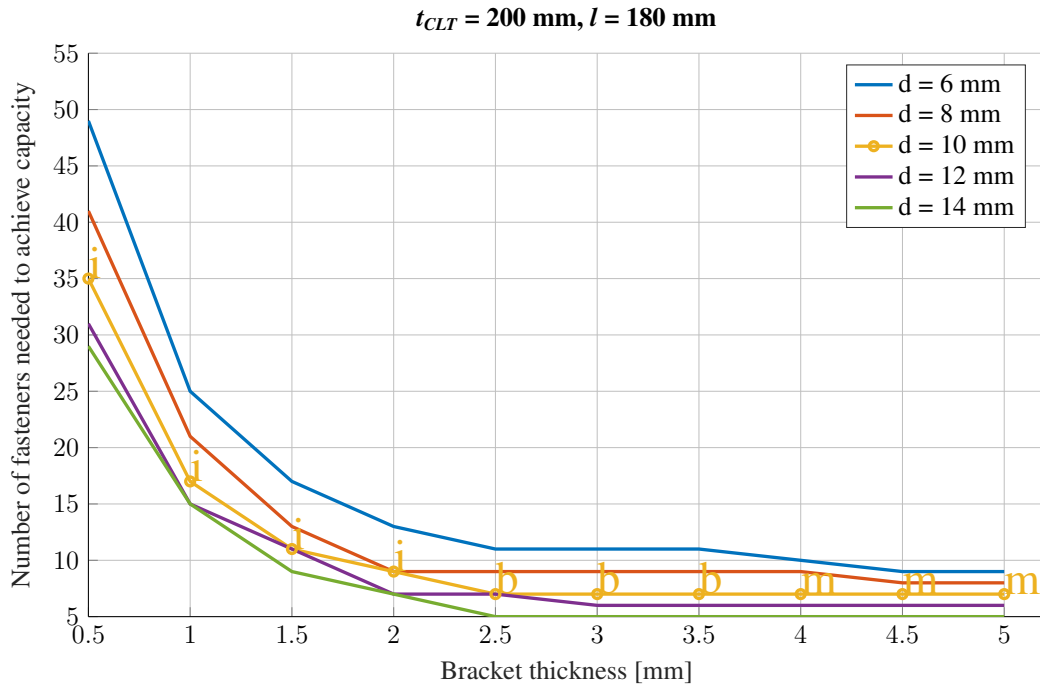


Figure H.7: Required number of 180 mm long fasteners to carry the design load from the case study, with the rope effect excluded, shown for various fastener diameters and plate thicknesses, with a CLT thickness of 200 mm. For readability, governing failure modes are indicated only for the 10 mm diameter screw. See Table 4.2 for a description of the failure modes.

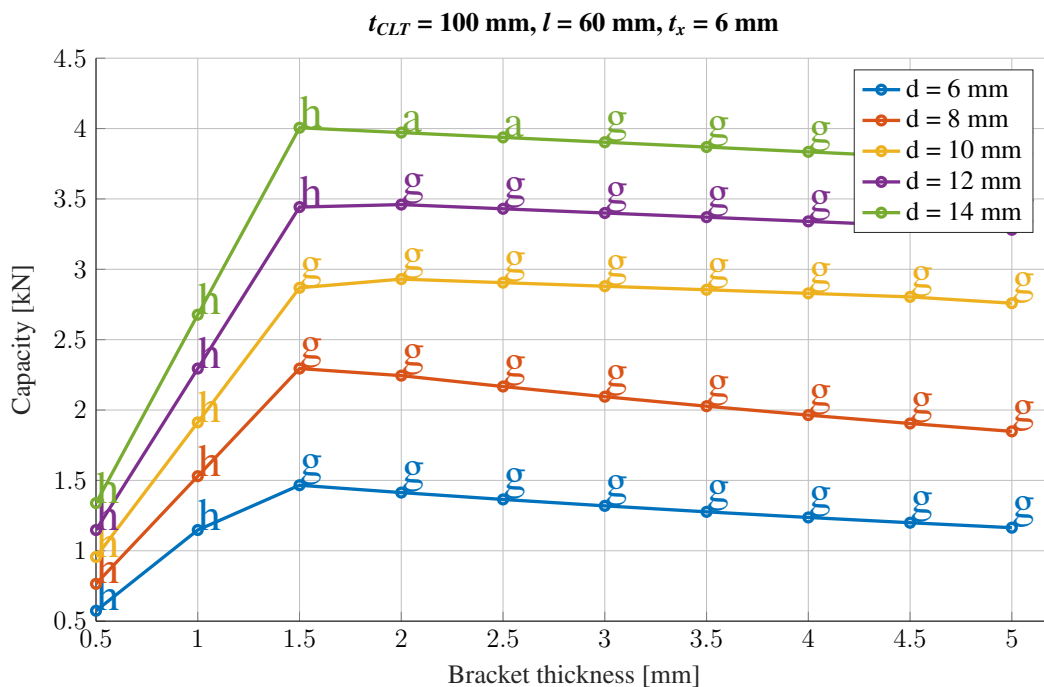


Figure H.8: Load-carrying capacity per 60 mm long fastener, with 6 mm xylomer included, for various fastener diameters and plate thicknesses, with a CLT thickness of 100 mm. Governing failure modes are indicated according to Table 4.2.

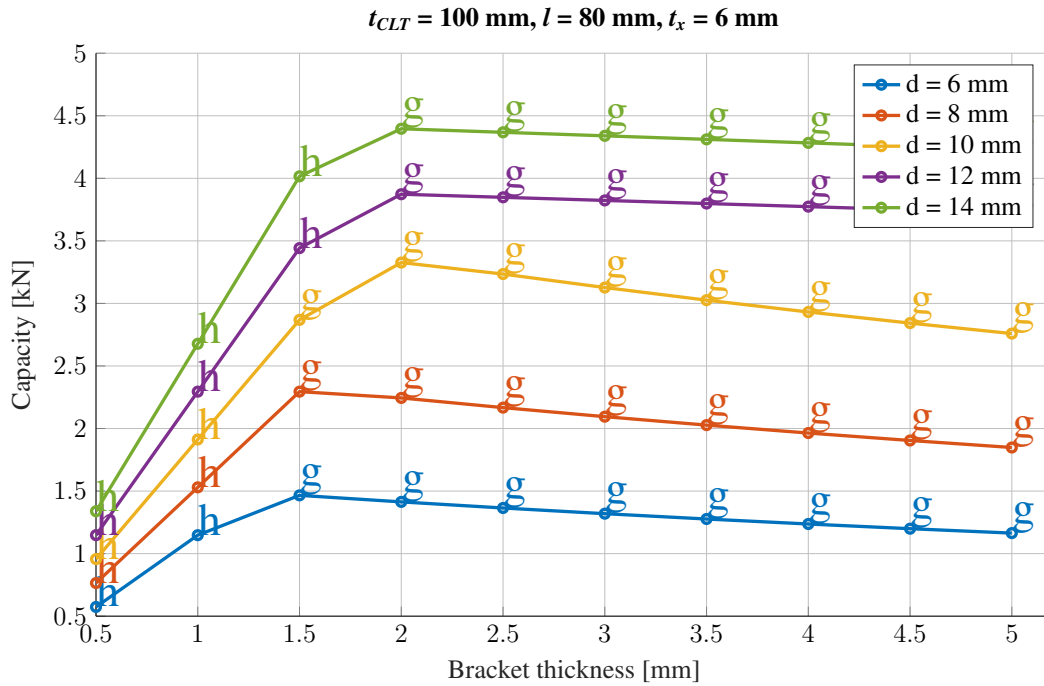


Figure H.9: Load-carrying capacity per 80 mm long fastener, with 6 mm xylomer included, for various fastener diameters and plate thicknesses, with a CLT thickness of 100 mm. Governing failure modes are indicated according to Table 4.2.

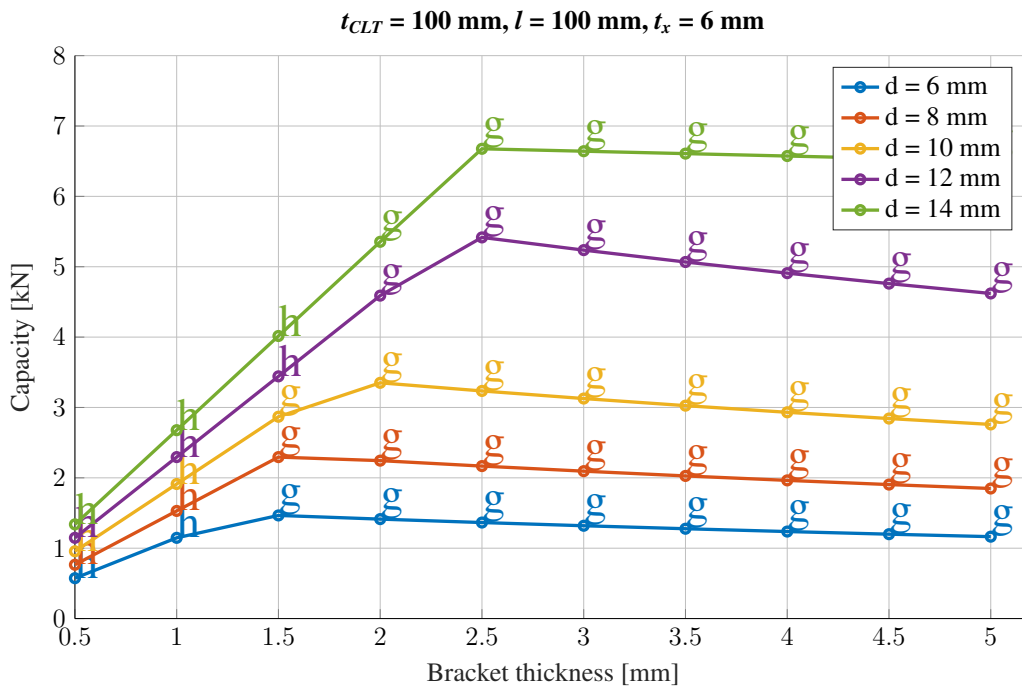


Figure H.10: Load-carrying capacity per 100 mm long fastener, with 6 mm xylomer included, for various fastener diameters and plate thicknesses, with a CLT thickness of 200 mm. Governing failure modes are indicated according to Table 4.2.

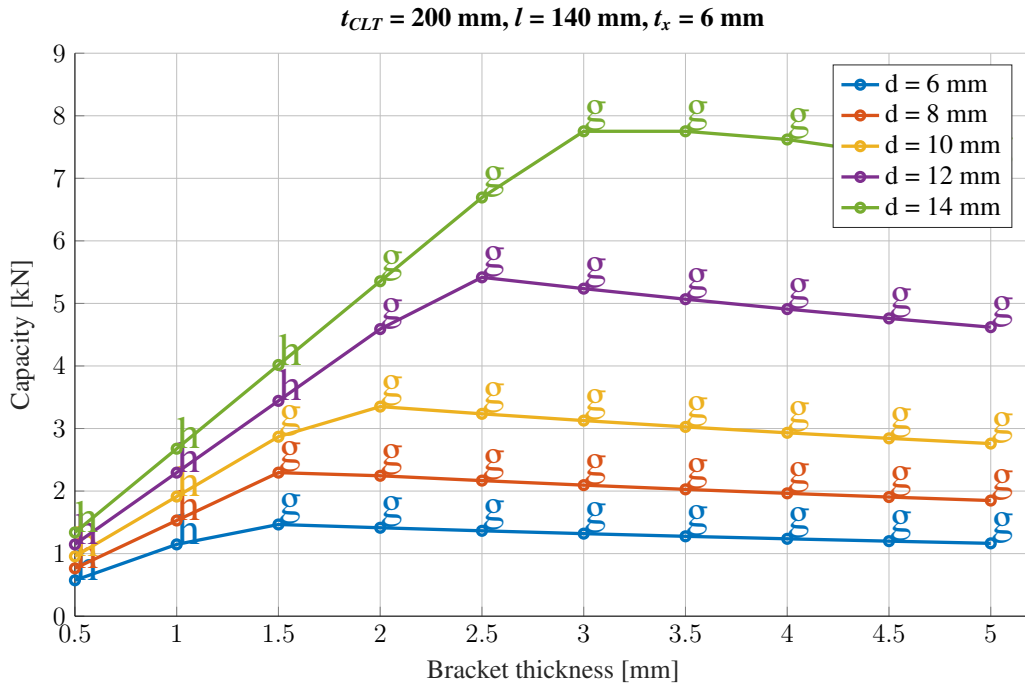


Figure H.11: Load-carrying capacity per 140 mm long fastener, with 6 mm xylomer included, for various fastener diameters and plate thicknesses, with a CLT thickness of 200 mm. Governing failure modes are indicated according to Table 4.2.

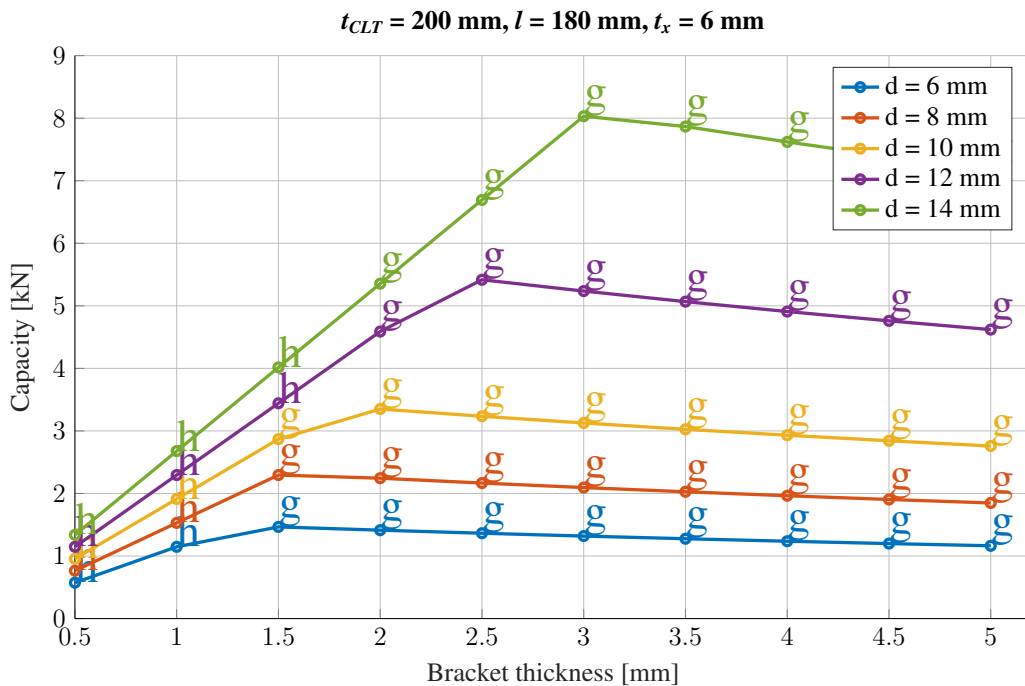


Figure H.12: Load-carrying capacity per 180 mm long fastener, with 6 mm xylomer included, for various fastener diameters and plate thicknesses, with a CLT thickness of 200 mm. Governing failure modes are indicated according to Table 4.2.

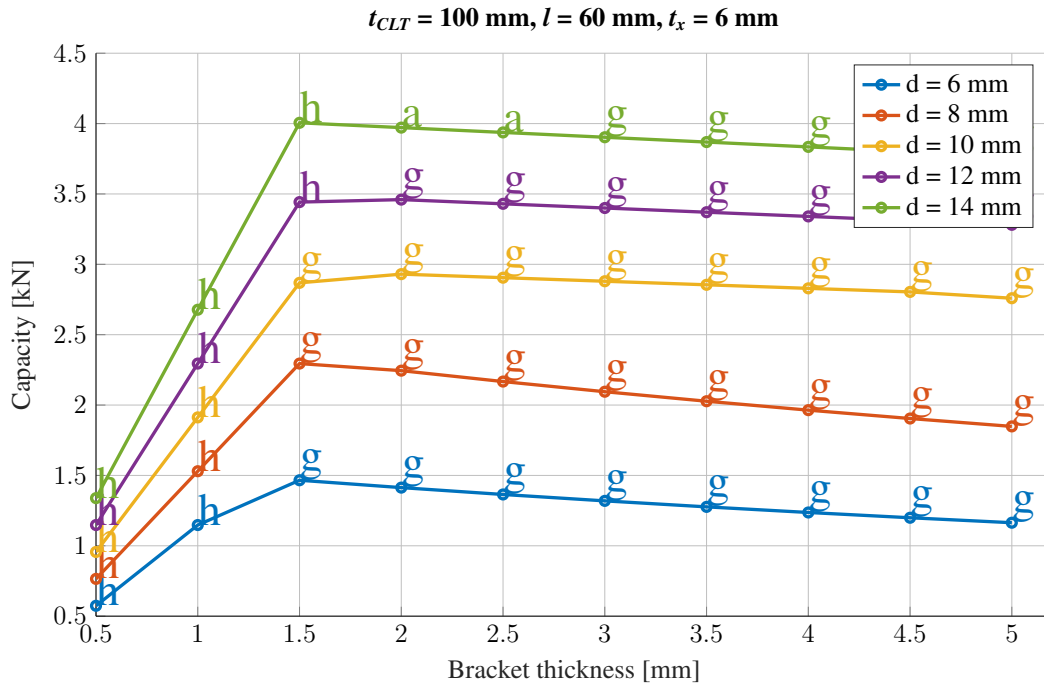


Figure H.13: Load-carrying capacity per 60 mm long fastener, with the rope effect excluded and with 6 mm xylomer included, for various fastener diameters and plate thicknesses, with a CLT thickness of 100 mm. Governing failure modes are indicated according to Table 4.2.

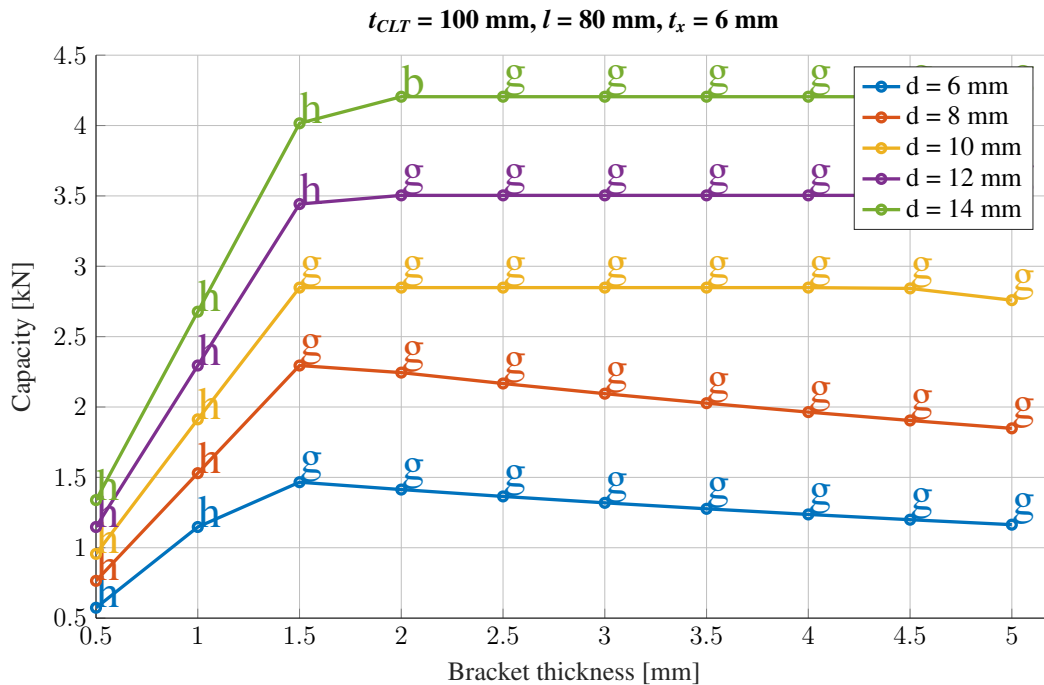


Figure H.14: Load-carrying capacity per 80 mm long fastener, with the rope effect excluded and with 6 mm xylomer included, for various fastener diameters and plate thicknesses, with a CLT thickness of 100 mm. Governing failure modes are indicated according to Table 4.2.

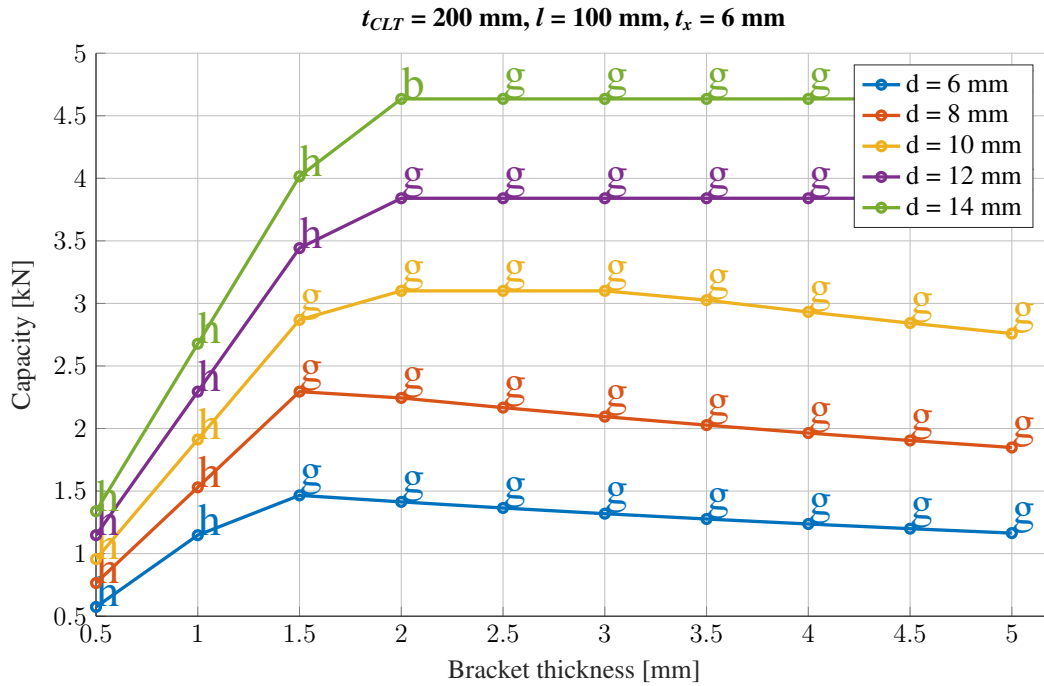


Figure H.15: Load-carrying capacity per 100 mm long fastener, with the rope effect excluded and with 6 mm xylomer included, for various fastener diameters and plate thicknesses, with a CLT thickness of 200 mm. Governing failure modes are indicated according to Table 4.2.

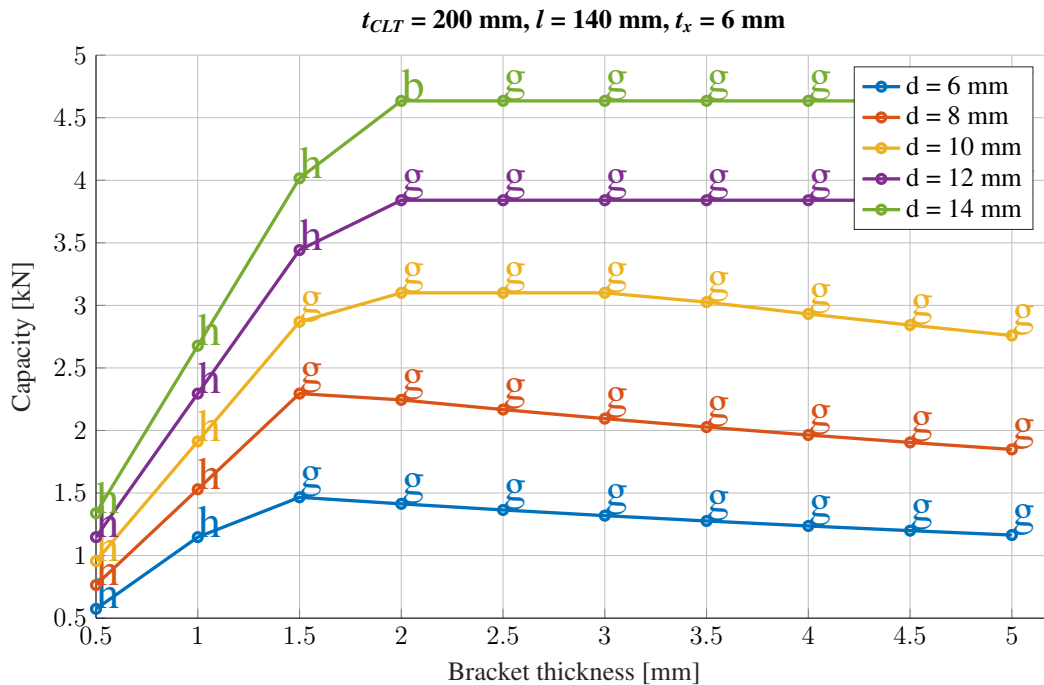


Figure H.16: Load-carrying capacity per 140 mm long fastener, with the rope effect excluded and with 6 mm xylomer included, for various fastener diameters and plate thicknesses, with a CLT thickness of 200 mm. Governing failure modes are indicated according to Table 4.2.

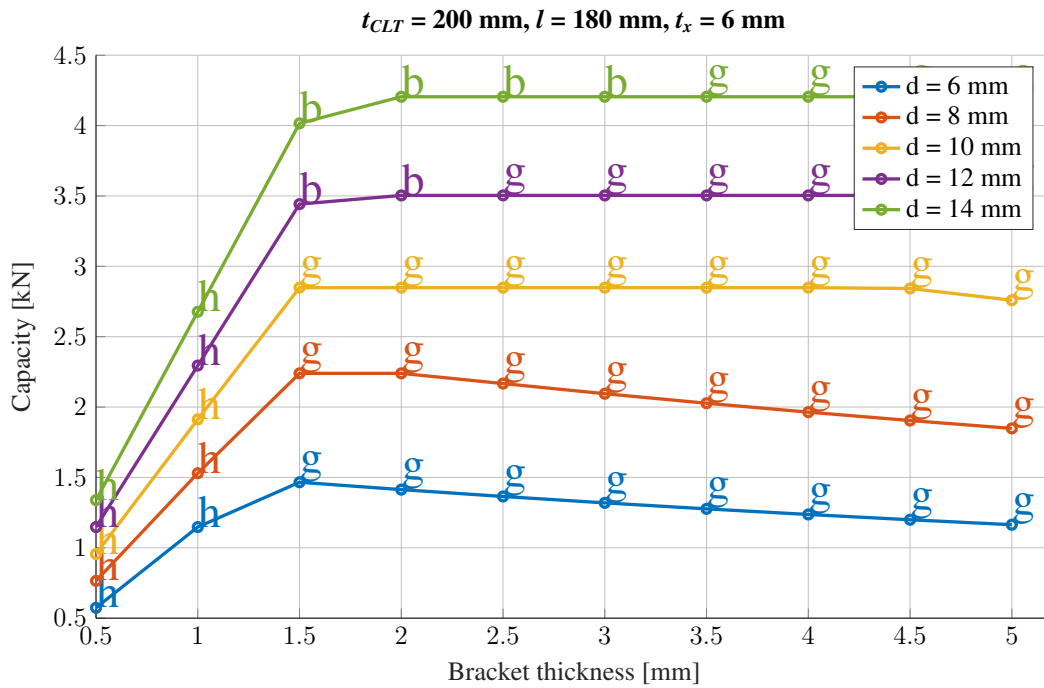


Figure H.17: Load-carrying capacity per 180 mm long fastener, with the rope effect excluded and with 6 mm xylomer included, for various fastener diameters and plate thicknesses, with a CLT thickness of 200 mm. Governing failure modes are indicated according to Table 4.2.

I MATLAB - Genetic algorithm

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```
clear all; clc;

% Genetic algorithm

% Permanent input variables
global lef_limit_1 lef_limit_2 t_CLT_1 t_CLT_2 k_T tx✓
alpha_load alpha_screw Load N_brackets
global fyb fub fu fy rho_k kmod gamma_M gamma_M0 gamma_M2✓
gamma_Rd screw

%Variable input parameters
global SCREW_INDEX_1 SCREW_INDEX_2 T_BRACKET

%Permanent input variables
lef_limit_1 = 80; lef_limit_2 = 110; % Thickness of 3 board✓
layers in CLT
t_CLT_1 = 140; t_CLT_2 = 180; % Actual thickness of entire✓
CLT
k_T = 0; % 1 for with rope effect, 0 for without rope✓
effect
tx = 6; %Either with no xylomer or 6 mm xylomer
alpha_load = pi/2; % Load direction relative grain
alpha_screw = pi/2; % Screw direction relative grain
Load = 48.9*1.5; % Design load
N_brackets = 4; % # of brackets
fyb = 900; fub = 1000; % MPa
fu = 430; fy = 275; % MPa
rho_k = 350; % kg/m^3
kmod = 0.9; gamma_M = 1.3; gamma_M0 = 1.0; gamma_M2 = 1.25;✓
gamma_Rd = 1.0;

% Screw parameters taken from retailer [d, l, lef, dh, d1,✓
ds, d0, Ft_Rk,
% F_withdrawal_Rk]
screw = [5 50 30 9.65 3.4 3.65 7 7.9 1.89;
         5 60 35 9.65 3.4 3.65 7 7.9 2.21;
         5 70 40 9.65 3.4 3.65 7 7.9 2.53;
```

```
5 80 50 9.65 3.4 3.65 7 7.9 3.16;
6 80 50 12 3.95 4.3 9 11.3 3.79;
6 90 55 12 3.95 4.3 9 11.3 4.17;
8 60 52 13.5 5.9 6.3 11 32 4.49;
8 80 55 13.5 5.9 6.3 11 32 5.15;
8 100 75 13.5 5.9 6.3 11 32 7.02;
8 120 95 13.5 5.9 6.3 11 32 8.89;
8 140 110 13.5 5.9 6.3 11 32 10.3;
8 160 130 13.5 5.9 6.3 11 32 12.17;
10 80 60 16.5 6.6 7.2 13 40 7.02;
10 100 75 16.5 6.6 7.2 13 40 8.78;
10 120 95 16.5 6.6 7.2 13 40 11.12;
10 140 110 16.5 6.6 7.2 13 40 12.87;
10 160 130 16.5 6.6 7.2 13 40 15.21;
10 180 150 16.5 6.6 7.2 13 40 17.55;
12 100 75 18.5 7.3 8.55 14 50 10.53;
12 120 90 18.5 7.3 8.55 14 50 12.64;
12 140 110 18.5 7.3 8.55 14 50 15.44;
12 160 120 18.5 7.3 8.55 14 50 16.85;
12 180 140 18.5 7.3 8.55 14 50 19.66;
12 200 160 18.5 7.3 8.55 14 50 22.46];
```

```
%Formulating the optimization problem
```

```
% In total there are three GA variables, d (screw
diameter), l (screw
% length) and t_bracket (bracket thickness). Since l is
dependent on d,
% these variables has been "packaged" into one single
variable which represent an index in a matrix.
nvars=3;
```

```
%All GA variables are discrete. Two sets of screw variables
are generated in total,
%one for the part connecting to the wall, one for the part
connecting to
%the floor
```

```

SCREW_INDEX_1 = [1:24]; % Screw index correspond to both ✓
diameter and length
SCREW_INDEX_2 = [1:24];
T_BRACKET = [1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6]; % ✓
Thicknesses of brackets

% Lower and upper bounds.
LB=ones(1,nvars);
UB=zeros(1,nvars);
UB(1)=numel(SCREW_INDEX_1);
UB(2)=numel(SCREW_INDEX_2);
UB(3)=numel(T_BRACKET);

% Initial guesses
for i = 1:nvars
    X0(i) = 1;
end

% Options for the optimization
options = optimoptions(@ga, ...
    'PopulationSize', nvars*100, ... %should ✓
be nvars*100
    'MaxGenerations', 200, ... %should be ✓
nvars*50
    'EliteCount', round(0.1*nvars*100), ✓
...%50
    'FunctionTolerance', 1e-9, ...
    'PlotFcn', {@gaplotbestf}, ...
    'ConstraintTolerance', 1e-2, ...
    'InitialPopulationMatrix', X0);

% The Objective function (also known as Fitness function) ✓
and the
% Constraint function.
ObjFcn= @Shear_FitnessFunc_Price;
ConsFcn= @Shear_constraints;

```

```
% The Genetic Algorithm which will generate the optimal
screw diameter and
% length, and bracket thickness based on price and number
of fasteners,
% with regard to constraints.
[x,fval,exitflag] = ga (ObjFcn, nvars, [], [], [], [], LB,
UB, ConsFcn, 1:nvars, options)

[Optimization_factor Price N_screws_1 N_screws_2 B P H
Fv_Rd_min Fv_Rd_1 Fv_Rd_2] = Shear_FitnessFunc_Price(x)

% Display results
title=["d_1" "l_1" "N_screws_1" "d_2" "l_2" "N_screws_2"
"B" "P" "H" "T_BRACKET" "Price" "Exitflag"];
values = num2cell([screw(x(1),1) screw(x(1),2) N_screws_1
screw(x(2),1) screw(x(2),2) N_screws_2 ceil(B) ceil(P) ceil
(H) T_BRACKET(x(3)) Price exitflag]);
table = cell2table(values, 'VariableNames', cellstr
(title'))

% Warning for when constraints are violated
[c_final, ~] = Shear_constraints(x);
if any(c_final > 0)
    warning('Final solution violates constraints!');
else
    disp('Final solution is feasible. ');
end
```

```
function [Optimization_factor Price N_screws_1 N_screws_2 B  
P H Fv_Rd_min Fv_Rd_1 Fv_Rd_2] = Shear_FitnessFunc_Price  
(x)
```

```
% This objective function calculates the price and the  
optimization factor
```

```
% of the connection for the given parameters x.
```

```
global T_BRACKET
```

```
% Calculating configuration connecting to the wall, based  
on parameter x.
```

```
[B P l_1 N_screws_1 Failure_Mode_1 d0_1 Fv_Rd_1] =  
Shear_GetBP(x);
```

```
% Calculating configuration connecting to the floor, based  
on parameter x
```

```
% and set width of bracket from previous calculation
```

```
[H l_2 N_screws_2 Failure_Mode_2 Fv_Rd_min d0_2 Fv_Rd_2] =  
Shear_GetH(x,B);
```

```
% Price of screws according to retailer
```

```
SCREW_PRICE = [0.896;  
0.96;  
1.256;  
1.496;  
1.728;  
1.936;  
1.916;  
2.508;  
3.328;  
3.664;  
4.504;  
4.78;  
3.176;  
5.204;  
5.764;  
7.22;
```

```
9.56;
10.96;
10.32;
13.32;
13.04;
14.56;
15.88;
17.64];

% Price of bracket in sek/mm^3 (Based on case study
references)
BRACKET_PRICE = 0.0008494;

MaterialPrice_1 = N_screws_1*SCREW_PRICE(x(1),1);
MaterialPrice_2 = N_screws_2*SCREW_PRICE(x(2),1);
MaterialPrice_bracket = ( B*P - d0_1^2*pi/4*N_screws_1 +
B*H - d0_2^2*pi/4*N_screws_2 )*T_BRACKET(x(3))
*BRACKET_PRICE;

% Total price for material
Price = MaterialPrice_1 + MaterialPrice_2 +
MaterialPrice_bracket;

% Optimization factor
Optimization_factor = Price * (N_screws_1 + N_screws_2);
```

```

function [c,c_eq] = Shear_constraints(x)

% This function formulates the constraints which will limit
the available
% solutions.
global lef_limit_1 lef_limit_2 t_CLT_1 t_CLT_2 k_T
alpha_load alpha_screw
global Load N_brackets Ft_Rk fub fu fy rho_k kmod gamma_M
gamma_M0
global gamma_M2 gamma_Rd screw SCREW_INDEX_1 SCREW_INDEX_2
T_BRACKET

% Function which design the bracket
[B P l_1 N_screws_1 Failure_Mode_1 d0_1 Fv_Rd_1] =
Shear_GetBP(x) ;
[H l_2 N_screws_2 Failure_Mode_2 Fv_Rd_min d0_2 Fv_Rd_2] =
Shear_GetH(x,B);

% First constraint checks so length of screw isn't larger
than (thickness of
% CLT-20mm)
Const(1) = l_1 - (t_CLT_1-20);
Const(2) = l_2 - (t_CLT_2-20);

% Second constraint checks failure mode och only allow
failure mode h and
% i.
if strcmp(Failure_Mode_1, 'h')
    Const(3) = -1;
elseif strcmp(Failure_Mode_1, 'i')
    Const(3) = -1;
else
    Const(3) = 1;
end
if strcmp(Failure_Mode_2, 'h')
    Const(4) = -1;
elseif strcmp(Failure_Mode_2, 'i')

```

```
        Const(4) = -1;
else
        Const(4) = 1;
end

% Third constraint limits width of the bracket to
reasonable width
% according to retailing brackets.
B_limit = 240;
if B < B_limit
        Const(5) = -1;
else
        Const(5) = 1;
end

% Fourth constraint checking if bracket is able to carry
the load.
if Fv_Rd_min >= Load/N_brackets
        Const(6) = -1;
else
        Const(6) = 1;
end
c=Const;
c_eq = [];
end
```

```
function [B P l_1 N_screws_1 Failure_Mode_1 d0 Fv_Rd] =✓  
Shear_GetBP(x)  %%%%%%%%%  
  
% This function contains all the capacity calculations and✓  
returns geometry  
% of the bracket and screw aswells as the governing failure✓  
mode for the  
% part of the bracket connecting to the wall.  
  
global lef_limit_1 t_CLT_1 k_T tx alpha_load alpha_screw✓  
Load N_brackets  
global fub fu fy rho_k kmod gamma_M gamma_M0 gamma_M2✓  
gamma_Rd screw  
global T_BRACKET  
  
% Parameters for the screw, bracket and CLT.  
d = screw(x(1),1);  
l_1 = screw(x(1),2);  
lef = screw(x(1),3);  
dh = screw(x(1),4);  
d1 = screw(x(1),5);  
ds = screw(x(1),6);  
d0 = screw(x(1),7);  
Ft_Rk = screw(x(1),8);  
F_withdrawal_Rk = screw(x(1),9);  
t_bracket = T_BRACKET(x(3));  
S = t_bracket;  
t_CLT = t_CLT_1;  
lef_limit = lef_limit_1;  
  
% Start with 1 row of screws with only 1 screw  
N_screws_1 = 1;  
n_rows_1 = 1;  
  
% Assuming a width-height-ratio of the bracket, based on a✓  
referenced  
% bracket
```

```
BP_ratio_ref = 240/83;

% Fastener geometry and properties
t1 = l_1 - S; % Penetration of entire screw in timber
A = pi * (ds^2) / 4; % Gross area of screw

% Bracket geometry
p1 = 2.2*d0; % mm (Tabel 3.3 in EN1993-1-8)
p2 = 2.4*d0; % mm (Tabel 3.3 in EN1993-1-8)
e1 = 1.2*d0; % mm (Tabel 3.3 in EN1993-1-8)
e2 = 1.2*d0; % mm (Tabel 3.3 in EN1993-1-8)

% Determining effective diameter
if (ds == d) && (l_1-lef >= 4*d)
    d_ef = ds;
else
    d_ef = 1.1*d1;
end

% Determining screw type
if d <= 6
    Type = '1.12';
elseif lef < lef_limit
    Type = '1.22';
else
    Type = '1.21';
end

% Embedment Strength (MPa), depending on screw type.
if Type == '1.11'
    fh_k = 0.082*(1-0.01*d_ef)*rho_k;
elseif Type == '1.12'
    fh_k = 0.082 * rho_k * d_ef^(-0.3);
elseif Type == '1.21'
    fh_k = 0.019 * min(d1, ds)^(-0.3) * rho_k^1.24;
elseif Type == '1.22'
    fh_k = 0.082*(1-0.01*d_ef)*rho_k / ((1.35+0.015*d_ef)*
```

```

((sin(alpha_load)^2+(cos(alpha_load))^2));
else
    error('Wrong fastener type');
end

% Yield Moment of Fastener (N·mm).
My_Rk = 0.3 * fub * d_ef^2.6/1000;

% Withdrawal Capacity (kN), depending on screw type.
if any(strcmp(Type, {'1.11', '1.12'}))
    Fax_Rk = min(F_withdrawal_Rk, Ft_Rk);
elseif any(strcmp(Type, {'1.21', '1.22'}))
    if (d <= 12) && (0.6 <= d1/d) && (d1/d <= 0.75)
        Fax_Rk = min(0.52*d^(-0.5)*lef^(-0.1)*rho_k^(0.8) *
d * lef * min(d/8, 1) / (1.2*(cos(alpha_screw))^2 + (sin
(alpha_screw))^2)/1000, Ft_Rk);
    else
        Fax_Rk = min(F_withdrawal_Rk, Ft_Rk);
    end
else
    error('Wrong fastener type');
end

% Johansen's equations for lateral resistance (kN)
Fv_Rk_a = 0.4 * fh_k * t1 * d / 1000;
Fv_Rk_b = 1.15 * sqrt(2 * My_Rk * fh_k*10^6 * d/1000) /
1000;
Fv_Rk_c = fh_k * t1 * d / 1000 ;
Fv_Rk_d = fh_k*10^6 * t1/1000 * d/1000 * (sqrt(2 + 4 *
My_Rk / (fh_k*10^6 * d/1000 * (t1/1000)^2)) - 1) / 1000;
Fv_Rk_e = 2.3 * sqrt(My_Rk * fh_k*10^6 * d/1000) / 1000;

% Characteristic capacity per fastener [kN], determined by
% thickness of plate and diameter
if S <= 0.5 * d
    Fv_Rk_EYM = min([Fv_Rk_a, Fv_Rk_b + min(Fax_Rk/4,
Fv_Rk_b*k_T)]);

```

```

    if Fv_Rk_EYM == Fv_Rk_a
        Fv_Rk_EYM_index = 'a';
    else
        Fv_Rk_EYM_index = 'b';
    end
elseif S >= d
    Fv_Rk_EYM = min([Fv_Rk_c, Fv_Rk_d + min(Fax_Rk/4,
Fv_Rk_d*k_T), Fv_Rk_e + min(Fax_Rk/4, Fv_Rk_e*k_T)]);
    if Fv_Rk_EYM == Fv_Rk_c
        Fv_Rk_EYM_index = 'c';
    elseif Fv_Rk_EYM == Fv_Rk_d + min(Fax_Rk/4,
Fv_Rk_d*k_T)
        Fv_Rk_EYM_index = 'd';
    else
        Fv_Rk_EYM_index = 'e';
    end
else
    Fv_Rk_EYM = min([Fv_Rk_a, Fv_Rk_b + min(Fax_Rk/4,
Fv_Rk_b*k_T)]) + abs(min([Fv_Rk_a, Fv_Rk_b + min(Fax_Rk/4,
Fv_Rk_b*k_T)]) - min([Fv_Rk_c, Fv_Rk_d + min(Fax_Rk/4,
Fv_Rk_d*k_T), Fv_Rk_e + min(Fax_Rk/4, Fv_Rk_e*k_T)])) * (S-
0.5*d)/(0.5*d);
    Fv_Rk_EYM_index = 'm';
end

% Shear failure of fastener [kN]
Fv_Rk_f = 0.6 * fub * A * 1/1000;

% Bending failure of fastener [kN]
Fb_Rk_g = (fub * pi * ((ds/2)^3/4)) / (tx + S/2) *
(1/1000);

% Bearing failure in bracket [kN]
alpha_b = min([e1/(3*d0), p1/(3*d0), 1, fub/fu]);
k1 = min([2.8 * e2/d0 - 1.7, 1.4 * p2/d0, 2.5]);
Fv_Rk_h = k1 * alpha_b * fu * d * S * (1/1000);

```

```

% Design capacities
Fv_Rd_EYM = Fv_Rk_EYM * kmod / gamma_M;
Fv_Rd_f = Fv_Rk_f / gamma_M2;
Fb_Rd_g = Fb_Rk_g / gamma_M2;
Fv_Rd_h = Fv_Rk_h / gamma_M2 ;

% Design bracket according to shear failure and checking if
all
% failure modes can achieve design load.

while true

    % Shear failure in bracket [kN]

    % While-loop which adds rows if bracket is to wide,
based on assumed
    % BP_ratio
    while true
        B = 2*e1 + (ceil(N_screws_1/n_rows_1)-1)*p1; %
Width of bracket
        P = 2*e2+(n_rows_1-1)*p2; % Height of bracket
        if B/P <= 1.2*BP_ratio_ref % (Bracket cannot have a
BP_ratio which is 20% higher than reference bracket)
            break
        end
        n_rows_1 = n_rows_1 + 1;
    end

    Av = (B - d0*ceil(N_screws_1/n_rows_1)) * S; % Shear
area of bracket
    Vc_Rk_i = Av * fy / sqrt(3) * (1/1000);
    Vc_Rd_i = Vc_Rk_i / gamma_M0 ; % Design shear capacity
of bracket

    Fv_Rd = [
        Fv_Rd_EYM*N_screws_1/gamma_Rd;
        Fv_Rd_f*N_screws_1/gamma_Rd;

```

```
Fb_Rd_g*N_screws_1/gamma_Rd;
Fv_Rd_h*N_screws_1;
Vc_Rd_i
];

% Checking if minimum capacity is enough for design load. If not,
% checking if more shear area or screws are needed.
Fv_Rd_min = min(Fv_Rd);
if Fv_Rd_min >= Load/4
    break;
elseif Fv_Rd_min == Vc_Rd_i
    p1 = p1*1.01;
else
    N_screws_1 = N_screws_1 + 1;
end
end

% Marking which failure mode is governing for each combination of
% diameter and plate thickness (For a entire connection)
if min(Fv_Rd) == Fv_Rd(1)
    Fd_min_index = Fv_Rk_EYM_index;
elseif min(Fv_Rd) == Fv_Rd(2)
    Fd_min_index = 'f';
elseif min(Fv_Rd) == Fv_Rd(3)
    Fd_min_index = 'g';
elseif min(Fv_Rd) == Fv_Rd(4)
    Fd_min_index = 'h';
else
    Fd_min_index = 'i';
end
Failure_Mode_1 = Fd_min_index;
end
```

```
function [H l_2 N_screws_2 Failure_Mode_2 Fv_Rd_min d0
Fv_Rd] = Shear_GetH(x,B)

% This function contains all the capacity calculations and
returns geometry
% of the bracket and screw aswells as the governing failure
mode for the
% part of the bracket connecting to the floor
global lef_limit_2 t_CLT_2 k_T tx alpha_load alpha_screw
Load N_brackets
global fub fu fy rho_k kmod gamma_M gamma_M0 gamma_M2
gamma_Rd screw
global T_BRACKET

% Parameters for the screw, bracket and CLT.
d = screw(x(2),1);
l_2 = screw(x(2),2);
lef = screw(x(2),3);
dh = screw(x(2),4);
d1 = screw(x(2),5);
ds = screw(x(2),6);
d0 = screw(x(2),7);
Ft_Rk = screw(x(2),8);
F_withdrawal_Rk = screw(x(2),9);
t_bracket = T_BRACKET(x(3));
S = t_bracket;
t_CLT = t_CLT_2;
lef_limit = lef_limit_2;

% Start with 1 row of screws with only 1 screw
N_screws_2 = 1;
n_rows_2 = 1;

% Assuming a width-height-ratio of the bracket, based on a
referenced
% bracket
BP_ratio_ref = 240/83;
```

```
% Fastener geometry and properties
t1 = l_2 - S; % Penetration of entire screw in timber
A = pi * (ds^2) / 4; % Gross area of screw

% Bracket geometry
p1 = 2.2*d0; % mm (Tabel 3.3 in EN1993-1-8)
p2 = 2.4*d0; % mm (Tabel 3.3 in EN1993-1-8)
e1 = 1.2*d0; % mm (Tabel 3.3 in EN1993-1-8)
e2 = 1.2*d0; % mm (Tabel 3.3 in EN1993-1-8)

% Determining effective diameter
if (ds == d) && (l_2-lef >= 4*d)
    d_ef = ds;
else
    d_ef = 1.1*d1;
end

% Determining screw type
if d <= 6
    Type = '1.12';
elseif lef < lef_limit
    Type = '1.22';
else
    Type = '1.21';
end

% Embedment Strength (MPa), depending on screw type.
if Type == '1.11'
    fh_k = 0.082*(1-0.01*d_ef)*rho_k
elseif Type == '1.12'
    fh_k = 0.082 * rho_k * d_ef^(-0.3);
elseif Type == '1.21'
    fh_k = 0.019 * min(d1, ds)^(-0.3) * rho_k^1.24;
elseif Type == '1.22'
    fh_k = 0.082*(1-0.01*d_ef)*rho_k / ((1.35+0.015*d_ef)*sqrt(
((sin(alpha_load)^2+(cos(alpha_load))^2)));
```

```

else
    error('Wrong fastener type');
end

% Yield Moment of Fastener (N·mm).
My_Rk = 0.3 * fub * d_ef^2.6/1000;

% Withdrawal Capacity (kN), depending on screw type.
if any(strcmp(Type, {'1.11', '1.12'}))
    Fax_Rk = min(F_withdrawal_Rk, Ft_Rk);
elseif any(strcmp(Type, {'1.21', '1.22'}))
    if (d <= 12) && (0.6 <= d1/d) && (d1/d <= 0.75)
        Fax_Rk = min(0.52*d^(-0.5)*lef^(-0.1)*rho_k^(0.8) *
d * lef * min(d/8, 1) / (1.2*(cos(alpha_screw))^2 + (sin
(alpha_screw))^2)/1000, Ft_Rk);
    else
        Fax_Rk = min(F_withdrawal_Rk, Ft_Rk);
    end
else
    error('Wrong fastener type');
end

% Johansen's equations for lateral resistance (kN)
Fv_Rk_a = 0.4 * fh_k * t1 * d / 1000;
Fv_Rk_b = 1.15 * sqrt(2 * My_Rk * fh_k*10^6 * d/1000) /
1000;
Fv_Rk_c = fh_k * t1 * d / 1000 ;
Fv_Rk_d = fh_k*10^6 * t1/1000 * d/1000 * (sqrt(2 + 4 *
My_Rk / (fh_k*10^6 * d/1000 * (t1/1000)^2)) - 1) / 1000;
Fv_Rk_e = 2.3 * sqrt(My_Rk * fh_k*10^6 * d/1000) / 1000;

% Characteristic capacity per fastener [kN], determined by
% thickness of plate and diameter
if S <= 0.5 * d
    Fv_Rk_EYM = min([Fv_Rk_a, Fv_Rk_b + min(Fax_Rk/4,
Fv_Rk_b*k_T)]);
    if Fv_Rk_EYM == Fv_Rk_a

```

```

        Fv_Rk_EYM_index = 'a';
    else
        Fv_Rk_EYM_index = 'b';
    end
elseif S >= d
    Fv_Rk_EYM = min([Fv_Rk_c, Fv_Rk_d + min(Fax_Rk/4, ✓
Fv_Rk_d*k_T), Fv_Rk_e + min(Fax_Rk/4, Fv_Rk_e*k_T)]);
    if Fv_Rk_EYM == Fv_Rk_c
        Fv_Rk_EYM_index = 'c';
    elseif Fv_Rk_EYM == Fv_Rk_d + min(Fax_Rk/4, ✓
Fv_Rk_d*k_T)
        Fv_Rk_EYM_index = 'd';
    else
        Fv_Rk_EYM_index = 'e';
    end
else
    Fv_Rk_EYM = min([Fv_Rk_a, Fv_Rk_b + min(Fax_Rk/4, ✓
Fv_Rk_b*k_T)]) + abs(min([Fv_Rk_a, Fv_Rk_b + min(Fax_Rk/4, ✓
Fv_Rk_b*k_T)]) - min([Fv_Rk_c, Fv_Rk_d + min(Fax_Rk/4, ✓
Fv_Rk_d*k_T), Fv_Rk_e + min(Fax_Rk/4, Fv_Rk_e*k_T)])) * (S-✓
0.5*d)/(0.5*d);
    Fv_Rk_EYM_index = 'm';
end

% Shear failure of fastener [kN]
Fv_Rk_f = 0.6 * fub * A * 1/1000;

% Bending failure of fastener [kN]
Fb_Rk_g = (fub * pi * ((ds/2)^3/4)) / (tx + S/2) * ✓
(1/1000);

% Bearing failure in bracket [kN]
alpha_b = min([e1/(3*d0), p1/(3*d0), 1, fub/fu]);
k1 = min([2.8 * e2/d0 - 1.7, 1.4 * p2/d0, 2.5]);
Fv_Rk_h = k1 * alpha_b * fu * d * S * (1/1000);

% Design capacities

```

```

Fv_Rd_EYM = Fv_Rk_EYM * kmod / gamma_M;
Fv_Rd_f = Fv_Rk_f / gamma_M2;
Fb_Rd_g = Fb_Rk_g / gamma_M2;
Fv_Rd_h = Fv_Rk_h / gamma_M2 ;

% Design bracket according to shear failure and checking if
all
% failure modes can achieve design load.

while true
    % Shear failure in bracket [kN]

    % While-loop which adds rows if bracket is to wide,
based on assumed
    % BP_ratio
    while true
        H = 2*e2+(n_rows_2-1)*p2; % Height of bracket
        if B/H <= 1.2*BP_ratio_ref % (Bracket cannot have a
BP_ratio which is 20% higher than reference bracket)
            if 2*e1 + (ceil(N_screws_2/n_rows_2)-1)*p1 <= B
                break
            else
                n_rows_2 = n_rows_2 + 1;
            end
        else
            n_rows_2 = n_rows_2 + 1;
        end
    end
end

Av = (B - d0*ceil(N_screws_2/n_rows_2)) * S; % Shear
area of bracket
Vc_Rk_i = Av * fy / sqrt(3) * (1/1000);
Vc_Rd_i = Vc_Rk_i / gamma_M0 ; % Design shear capacity
of bracket
Fv_Rd = [
    Fv_Rd_EYM*N_screws_2/gamma_Rd;
    Fv_Rd_f*N_screws_2/gamma_Rd;

```

```
Fb_Rd_g*N_screws_2/gamma_Rd;
Fv_Rd_h*N_screws_2;
Vc_Rd_i
];

% Checking if minimum capacity is enough for design load. If not,
% checking if more shear area or screws are needed.
Fv_Rd_min = min(Fv_Rd);
if Fv_Rd_min >= Load/4
    break;
elseif Fv_Rd_min == Vc_Rd_i
    break
else
    N_screws_2 = N_screws_2 + 1;
end
end

% Marking which failure mode is governing for each combination of
% diameter and plate thickness (For a entire connection)
if min(Fv_Rd) == Fv_Rd(1)
    Fd_min_index = Fv_Rk_EYM_index;
elseif min(Fv_Rd) == Fv_Rd(2)
    Fd_min_index = 'f';
elseif min(Fv_Rd) == Fv_Rd(3)
    Fd_min_index = 'g';
elseif min(Fv_Rd) == Fv_Rd(4)
    Fd_min_index = 'h';
else
    Fd_min_index = 'i';
end
Failure_Mode_2 = Fd_min_index;
end
```

