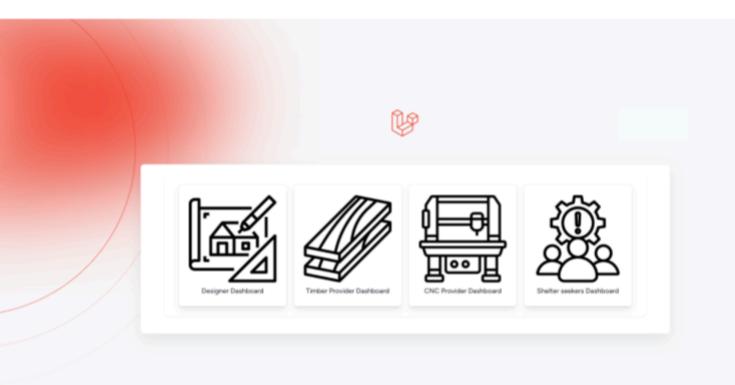
Lock n Load

A DIGITAL SOLUTION FOR EMERGENCY TIMBER SHELTERS



EMPOWERING DESIGNERS AND SEEKERS

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Abstract

This thesis delves into the potential of timber as a sustainable and efficient material for constructing emergency shelters, particularly in post-disaster scenarios where rapid and accessible housing solutions are critical. The research focuses on the development of "Lock n Load," a digital tool designed to streamline and optimize the design, construction, and delivery of timber frame shelters.

A primary challenge addressed in this thesis is the limited availability of skilled labor in post-disaster situations. "Lock n Load" tackles this challenge by automating complex design tasks, enabling individuals with minimal construction experience to participate in building their own shelters. The tool incorporates a user-friendly interface that simplifies the design process, making it accessible to a wider range of individuals.

Another key aspect of this research is the emphasis on utilizing readily available resources. By optimizing the use of timber and incorporating local sourcing, "Lock n Load" promotes sustainability and reduces reliance on external materials. This approach not only minimizes environmental impact but also allows for faster and more cost-effective shelter construction.

The research methodology includes a case study that investigates various design and optimization methods for timber structures. This case study provides insights into the structural performance and material efficiency of different timber frame designs, informing the development and refinement of "Lock n Load".

Lock n Load offers an innovative solution to address the urgent need for effective emergency shelters by bridging traditional timber construction with modern digital tools. "Lock n Load" empowers individuals to take an active role in their own shelter construction, promoting self-reliance and community participation in post-disaster recovery efforts. The tool's focus on sustainability, efficiency, and accessibility makes it a valuable resource in addressing the challenges of providing rapid and resilient housing solutions in times of crisis.

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List of Mathematical Symbols

 $\sigma_{c.o.d}$: Compressive stress

 $f_{c.o.d}$: Design compressive strength

 N_{ED} : Design axial compressive force

 \boldsymbol{k}_{mod} : Modification factor for the impact of load duration and moisture content

 $\mathbf{f}_{c.og}$: Characteristic compressive strength

 $y_{_M}$: Partial factor accounting for the material properties

 $\sigma_{m,v,d}$: The bending stress about the y-axis

 $f_{m,v,d}$: Bending strength

 $M_{y,ED}$: Bending moment around the y-axis

 w_{ij} : Section modulus about the y-axis

 $\mathbf{f}_{m,g,k}$: Characteristic bending strength

 au_d : The design shear stress

 f_{vd} : The design shear strength

 $v_{_{ED}}$: The design shear force

 $\mathbf{f}_{\boldsymbol{v},\boldsymbol{g},\boldsymbol{k}}$: The characteristic shear strength of timber

 k_{cr} : The factor for the potential cracking of the timber

 $\boldsymbol{\sigma}_{\!\!c.o.d}$: The design compressive stress acting on the timber

 $\mathbf{f}_{c,o,d}$ $% f_{c,o,d}$: The design compressive strength of the timber parallel to the grain.

: The modification factor for load duration and moisture content.

 $N_{_{FD}}$: The design axial force (compression)

 $f_{c.o.a.k}$: The characteristic bending strength of the timber

 $y_{_M}$: The partial safety factor for material properties

 $w_{creep,q}$: The creep deformation due to dead load

 $w_{inst.a}$: The immediate deflection under dead load

: The factor accounting for creep's influence under sustained load

 $w_{creep,lead}$: The Creep due to Live Load fo rLeading Variable Action

 $w_{creep,q}$: The creep deformation from leading variable action

 $w_{inst.a}$: The immediate deflection under leading variable action

 ψ_{acmp} : The factor adjusting for the loading duration for accompanying load Variable Action

 $w_{creep,acmp}$: The Creep due to Accompanying Variable Action

List of abbreviations

- CNC: Computer Numerical Control
- ESBM: Equivalent Steel Bolt Method
- FEM: Finite Element Model
- FEA: Finite Element Analysis
- MOE: Modulus of Elasticity
- MT: Mortise and tenon
- PMT: Pegged Mortise and tenon

Introduction

Shelter, more than just a physical structure, is fundamental to human well-being and a critical determinant of health outcomes (Shaw, 2004). It serves as a habitable sanctuary, offering security, privacy, and a sense of dignity to its occupants (Shelter Center, 2010). In the face of natural disasters – earthquakes, hurricanes, landslides, tornadoes, tsunamis, and typhoons – the vulnerability of developing countries is starkly exposed. Inadequate building practices and lax planning codes often render homes in these regions tragically susceptible to damage or complete destruction (Schilderman, 2004). The absence of timely and adequate emergency or temporary shelter can lead to the proliferation of overcrowded, and hoc dwellings. These makeshift settlements, while a testament to human resilience, frequently become breeding grounds for a host of health concerns (VanRooyen and Leaning, 2005). The escalating frequency of natural disasters, compounded by the effects of climate change and humanitarian crises, underscores the urgent and growing need for effective emergency shelter solutions worldwide, particularly for vulnerable populations (Allen, 2006; Ashton, 2000; Wilson, 2011).

Timber, with its unique blend of characteristics, emerges as a compelling option that addresses both the immediate and long-term needs of those affected. Historically, particularly in areas abundant in timber, farmers readily built their own shelter. This skill, passed down through generations, fostered a deep connection between them and their homes. The process was so commonplace that even traveling merchants in Russia carried tools to construct their own makeshift offices. Whether in the Carpathian Mountains, the Alps, or in Japan, self-built farm houses remained a tradition well into the 20th century, showcasing how easily accessible this practice was when timber was plentiful (Zwerger 2015).

Beyond the timber structure itself, the artistry of **joinery**, as ancient as history itself, especially in regions abundant in timber, played a crucial role in these self-built structures. For instance, the Potala Palace and Jokhang Temple in Tibet, built with methods dating back over 4500 years, still stand today. Likewise, the Dou-gong bracket system (figure 1.1) originating around 770 BC, continues to be used in traditional timber buildings throughout China, Korea, and Japan. Even in ancient Egypt, archaeological finds and artistic depictions reveal the use of woodworking tools like saws, chisels, and mallets, highlighting the long history of carpentry and joinery (Arlet 2021). In timber structures, connections play a crucial role in ensuring the overall strength, durability,

and effective load transfer of the entire system. Metal fasteners (figure 1.2) are currently the predominant method for joining timber components together. However, while joinery became obsolete because of its labor-intensive nature and the need for high-level skills, the advent of digital fabrication technologies has renewed interest in joinery (Siem 2017).

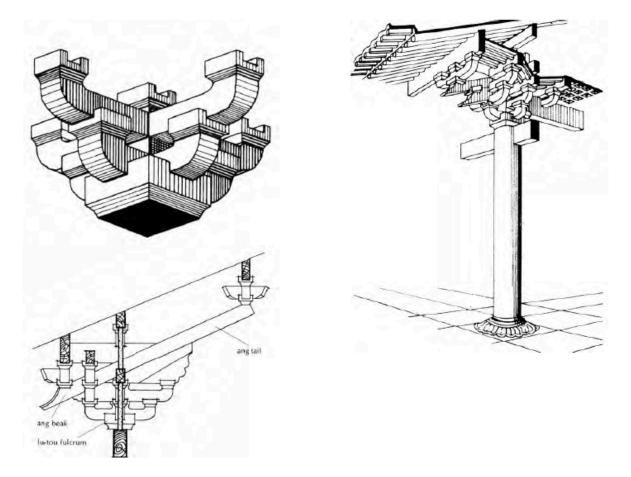


Figure 1.1: Dou-gong bracket system | Chinese architecture

Instances of recent connections can be seen in projects like the Yusuhara Wooden Bridge Museum in Japan (2010) by Kengo Kuma and Associates (figure 1.3), the Tamedia Office Building in Switzerland (2013) by Shigeru Ban Architects, and the Writers Theatre in the USA (2016) by Studio Gang Architects (Fang, Moradei et al. 2019). While the demand for carpenters skilled in manual joint carving is decreasing, there is a growing need for experts who can bridge the gap between traditional timber knowledge and modern construction practices (Hudert 2019).



Figure 1.2: examples of timber structures with steel connections a: (Gensler 2015), Matthew Millman Photography and b: Photo by Vermont Timber Works Inc.



Figure 1.3: Yusuhara Wooden Bridge Museum in Japan (2010) by Kengo Kuma and Associates

Rationale for Timber Shelters: Advantages and Opportunities

After a disaster, time is of the essence. Timber's **lightweight** nature and **prefabrication** potential allow for **rapid assembly** of shelters, ensuring that people are provided with a safe haven as quickly as possible. This swift response can be life-saving, particularly in harsh weather conditions or when access to affected areas is challenging (Falk 2019; Casagrande 2021; Barreca 2022). There are numerous examples of modern structures being rapidly constructed using wood (figure 1.4, figure 1.5).



Figure 1.4: The Rigot Collective Dwelling Centre in Geneva was built to quickly house 370 refugees. Constructed from prefabricated wooden modules, this two-building complex is designed to be taken down within ten years.

Another significant advantage inherent to timber structures, particularly those employing joinery, lies in their capacity for **non-destructive** assembly and their inherent compatibility with **Design for Deconstruction** principles. This potential for joinery to facilitate Design for Deconstruction stems directly from its characteristic of enabling non-destructive assembly, a feature not

typically encountered within the construction industry (Fang 2020). This inherent capacity for non-destructive assembly and Design for Deconstruction proves particularly advantageous in the context of temporary shelters. Such structures often require rapid deployment and eventual dismantling, making the ability to assemble and disassemble without damage or waste a critical factor.

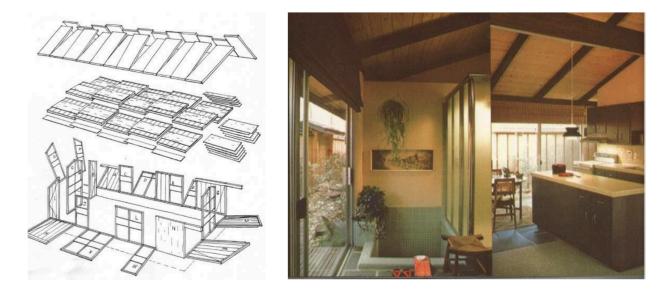


Figure 1.5: Techbuilt: Modern, Modular, Quick assembly and Made for the Masses

Another factor contributing to timber's suitability for emergency shelters is its **natural abundance**, **particularly in forested areas**. This readily available resource eliminates the need for extensive material transportation, allowing individuals to focus their efforts on shelter construction rather than resource acquisition.

Furthermore, timber's relatively soft nature allows for easy manipulation with **basic tools** (figure 1.6) commonly found in survival situations, enabling individuals to construct shelters rapidly and efficiently. This accessibility and ease of use make timber an invaluable resource in survival scenarios, where the need for shelter is often urgent and critical.

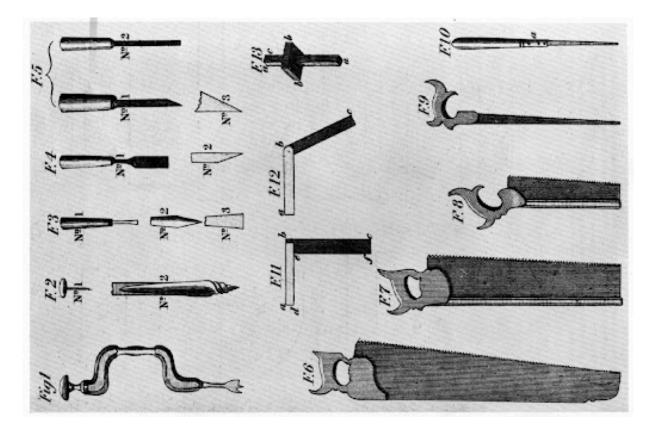


Figure 1.6: Simple tools used in timber framing

In addition, while timber's **environmental friendliness** may not be the primary reason for its use in emergency shelters, it's certainly a noteworthy benefit. As research like (Gustavsson 2006; Skog 2015; Stern 2018) shows, timber often boasts lower embodied carbon than traditional building materials, further enhancing its appeal. Also study by (Fang 2020) establishes the sustainability benefits of timber dry joints compared to conventional materials such as steel and concrete. The study demonstrates that employing interlocking joints as a building method holds significant potential for reducing the embodied carbon in structures. A key environmental distinction of timber lies in its adaptability, making it particularly valuable for emergency shelter construction. Unlike many short and mid-term shelter options that lack flexibility, timber structures can be disassembled, reused, and even upgraded to meet evolving needs, extending their lifespan and reducing waste. To fully utilize wood's benefits, we must extend its lifespan in buildings through adaptable designs or component reuse. However, current practices hinder this, necessitating a shift in building and product design to promote wood recycling (Hudert 2019). Given timber's **availability**, **adaptability**, **environmental benefits**, potential for **reuse**, **upgrade**, **rapid** and **low-dependency assembly**, it seems that timber-based structures present a promising solution to the escalating need for effective emergency and mid-term shelters in crisis situations.

Problem Statement

Though timber joinery and interlocking systems show great promise for improving emergency shelters, there are challenges to overcome before they become widely used.

However, various **obstacles** currently hinder the full realization of this vision:

While timber's abundance makes it an appealing construction material, its effective utilization demands more than mere availability. Designing **safe** and **resilient** timber structures necessitates a **profound understanding of structural engineering principles**. This entails not only a comprehensive grasp of **wood's diverse properties** and behaviors under stress but also proficiency in structural calculations and adherence to **building codes**.

The **intricate nature of timber** design further amplifies the **complexity**. Each structure, unique in its size, purpose, and environmental context, requires meticulous consideration. A well-conceived design, encompassing factors like foundation type and local climate, ensures the structure's longevity and functionality.

In the past, the knowledge of working with timber and constructing shelters was a **generational** inheritance. This knowledge encompassed an intuitive understanding of timber's properties, sizing rules-of-thumb, and climate-responsive design principles, refined through centuries of hands-on experience. Each generation contributed to an ongoing optimization process. (Zwerger 2015) . However, the advent of industrialization and modernism, accompanied by the rise of new materials, disrupted this lineage. The once-commonplace skills of timber construction were gradually eclipsed, creating a disconnect between people and their built environment. This loss of traditional knowledge represents a break in the **chain of experience**. Even in contemporary practice, timber joinery remains reliant on experiential knowledge. However, a disconnect exists between the design of timber joinery and that of other construction methods. No country has used structural reliability concepts for timber joint design equations, as **the safety levels** are hard to assess except for simple cases (Smith 2002). This is

different from wood member design, where reliability concepts are already used in several countries. While the sizing of timber members adheres to established structural analysis methods and material specifications, the detailing of joinery connections falls outside these codified boundaries. This necessitates reliance on engineering judgment and the builder's experiential knowledge, a practice that can introduce variability and uncertainty into the design process (Schmidt 2019). This **absence of standardized guidelines** and analytical methods for joinery connections hinders advancements in joinery design. The lack of a systematic framework limits the ability to rigorously assess the strength and stiffness of these connections, impeding innovation and optimization in timber construction (Shanks 2009).

The growing scale and complexity of modern wood construction demand a renewed focus on joinery design to facilitate **circularity**. Despite the potential for disassembly, reuse, and recycling offered by traditional principles, current practices often hinder achieving these goals. This necessitates a shift in design philosophy to **prioritize connections** that enable circular construction throughout the building lifecycle, from factory to site (Zwerger 2015).

In addition, the **need for optimisation** of the structural performance of temporary timber shelters was specifically underscored by the aftermath of the 2011 Great East Japan Earthquake. As survivors were compelled to live in temporary housing for durations far exceeding the initial two-year design period, these wooden units experienced significant deterioration, necessitating extensive repairs (Iwata 2023). The range of repair categories, from cracks in walls to damage to wooden foundations, highlights the necessity for a comprehensive database that not only records these issues but also facilitates the identification of future optimizations in timber shelters and structures. Beyond optimization for higher capacity, refining the construction process and accelerating the assembly of timber shelters, enhancing their overall livability emerges as another crucial objective.

In addition, the design of emergency shelters is inherently constrained by **contextual factors** that significantly impact their effectiveness and feasibility. Limited availability of materials, logistical complexities in transportation and deployment, and the need to adapt to diverse climatic conditions pose significant challenges to creating shelters that are both functional and resilient. These limitations necessitate innovative approaches that balance immediate needs with long-term sustainability, ensuring that emergency shelters are adaptable to the specific

context in which they are deployed.

Moreover, designing effective emergency shelters presents a significant challenge: balancing the diverse **personal preferences** of displaced individuals with the **constraints of limited resources** and **urgent needs**. What may be a suitable design for one person may not meet the needs of another, highlighting the complexities of delivering suitable shelters in times of crisis.

These obstacles underscore the challenges associated with the rapid deployment of timber shelter systems for structurally sound temporary shelters in post-disaster situations. To fully utilize the potential of timber shelter in disaster relief, it is crucial to address these challenges. This necessitates research into more efficient, integrated design methods and faster verification and optimizing processes, ultimately enabling the provision of timely, effective, and sustainable shelter solutions.

Research Objectives

The vision is to empower individuals to become active participants in assembling their own shelters, reducing reliance on specialized skills and labor. This approach would allow people to inhabit temporary, transitional, or even permanent structures that are **tailored to their needs** and preferences, to the greatest extent possible within the constraints of their circumstances.

The primary aim of this thesis is to develop a **digital tool** that **streamlines** and **enhances** the process of **delivering**, **designing**, **optimizing**, **provision** and **fabricating** post-disaster timber shelters for emergency use, benefiting disaster **victims**, shelter **designers**, **manufacturers** and other **stakeholders** involved in the **supply chain**.

Research Questions

Can a **digital tool** be created to **simplify**, **improve**, and **integrate** the process of **delivering**, **designing**, **optimizing**, and assembling post-disaster timber shelters for emergency use, providing benefits to **disaster victims**, **shelter designers**, and other key **stakeholders** in the **supply chain**? **How**?

Methodology

The research methodology consists of three distinct phases, **literature** and **background review**, **Case study**, and the **development** of the **tool** (Lock n Load).

literature review

The literature review begins with an exploration of **existing timber shelters** and structures, showcasing how others have navigated the challenges outlined in the problem statement. These examples highlight the key objectives for optimization. Subsequently, the investigation delves into the **properties** and **structural applications** of **timber**, providing a foundation for the design and parameters of the ensuing case study. Finally, the review explores the field of **timber structure optimization**, branching into **whole-structure optimization** and the **optimization of joints** and connections. These insights inform the methodological choices, design processes, and optimization strategies implemented in the case study.

Case study

The case study begins with the **preliminary design** of a timber frame, considering architectural and practical factors relevant to an emergency shelter. Next, Eurocode 5 guidelines are used to define the parameters and limitations for **optimizing** the **timber frame**. Once the most efficient cross-sections for the timber frame members are determined, the case study focuses on designing and optimizing the chosen connection: the pegged mortise and tenon joint. Two approaches are used to optimize this joint. First, an **analytical** method is developed, using a steel bolt equivalent model and iterative calculations to find the best joint dimensions. Then, a **numerical simulation** (**FEM**) is created to test and optimize the joint with a wider range of factors. The combination of these two optimization approaches led to the final design.

Development of Lock n Load (the Tool)

The tool's designer section was built upon the foundation of a single, optimized timber frame block from the case study. All necessary components for this block were developed in Python, showcasing how timber frame design and optimization can be largely **automated** and incorporated into a **design library** for further refinement. Additionally, a panel for **shelter-seekers** was created to allow for **customization** based on available resources and individual preferences. The **supply chain** component was also developed, integrating **manufacturers** and **timber providers** with the other two elements of the tool.

LOCK N LOAD: A DIGITAL SOLUTION FOR EMERGENCY TIMBER SHELTERS

Research outline

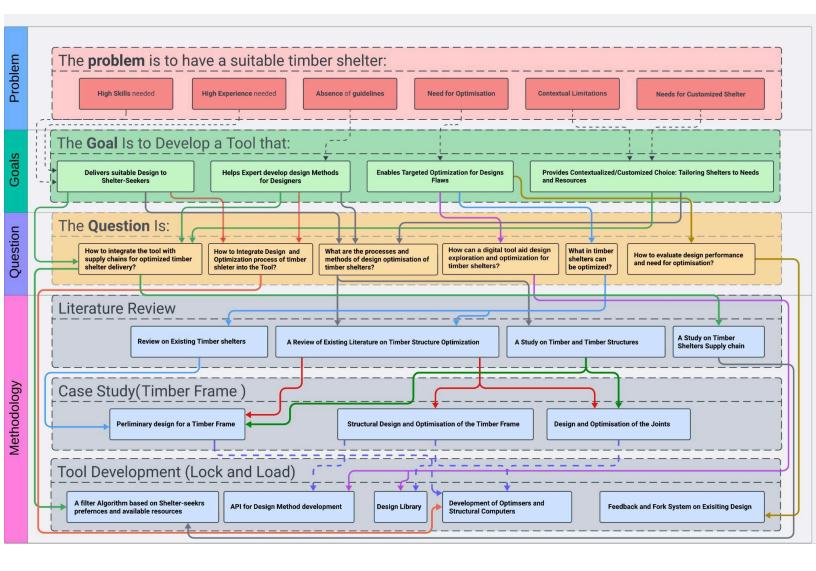


Figure 1.7: Research outline

"In the construction of houses, choice of woods is made. Straight un-knotted timber of good appearance is used for the revealed pillars, straight timber with small defects is used for the inner pillars. Timbers of the finest appearance, even if a little weak, are used for the thresholds, lintels, doors, and sliding doors, and so on. Good strong timber, though it be gnarled and knotted, can always be used discreetly in construction."

The Book of Five Rings: Miyamoto Musashi, 17th Century

Literature review

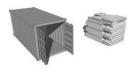
This section presents a review of existing timber shelters relevant to the thesis's research questions. Subsequently, a comprehensive examination of the literature concerning the analysis, simulation, and optimization of timber structures and their constituent components is provided.

Review of Existing Timber Shelters

This section explores existing timber shelters and structures, examining the **objectives** that designers prioritized during the optimization and design processes. By analyzing these choices, the key factors that contribute to the creation of a suitable and optimized timber shelter were determined.

Liina Transitional Shelter

The Liina Transitional Shelter (figure 2.1) was designed to address the immediate need for shelter in the aftermath of disasters. Its key features are its flat-pack shipping and rapid assembly, even in areas with limited infrastructure and resources. The design specifically avoids the need for complex tools, heavy machinery, or electricity, enabling deployment in challenging conditions (ArchDaily 2011).



Connect beams to level foundation



frame

Step 1: 6 panels assemble to make 1



2 flat-pack shelters fit in a standard shipping containe



Step 3: Tilt up the entire frame



Step 4: Slide in the end wall side pieces and attach the center fitting panel



Step 5: Make and tilt-up other frames



attach to foundation beams



Step 2: Tighten 2 liina around the top and bottom of the frame



Step 6: Make and tilt up the last house frame with shelf and tension strap

Total Time for Assembly:

15 minutes/frame 45 minutes/end wall 30 minutes/canvas 60 minutes/furniture

Total: 6 hours

Figure 2.1: Assembly diagram of the shelter, Liina team

The Liina Transitional Shelter's design prioritizes simplicity and ease of assembly in disaster zones. It utilizes standard nylon cargo straps and hollow core panels made from LVL frames and birch plywood. These panels are insulated with cellulose fiber and manufactured in dimensions that minimize waste, facilitate easy handling, and efficient shipping. The building assembly starts by creating a five-sided frame using panels connected with dowels. A cargo strap tightens the frame, driving dowels into adjacent panels and compressing gaskets for an airtight seal. The frame is then joined to others, forming parallel sections secured with the same method. A loft and end walls provide stability, and a tarpaulin offers weather protection. Extensive testing ensured the safety and durability of this simple yet unconventional system, leading to minor design refinements (Hudert 2019).

Glænø Stapel: Efficient Timber Shelter with Reciprocal Frames

The Glænø Stapel project (figure 2.2) in Denmark demonstrates a sustainable and innovative approach to agricultural building design. Challenging conventional methods that rely on prefabricated steel or timber trusses, the project utilized **locally sourced**, **lower-quality wood** to create an **optimized timber structure**.



Figure 2.2: Glænø Stapel

With inspiration from **reciprocal frames** (RFs), the design prioritized simplicity and **ease of construction**, employing **reversible connections** and **minimizing** the need for **heavy machinery**. Through meticulous **design iterations**, the **wood quantity** was optimized, resulting in a slender and elegant structure despite the use of lower-grade materials. The Glænø Stapel project demonstrates the feasibility of achieving structurally sound timber shelter using locally sourced, lower-quality wood, highlighting (Hudert 2019).

Timber-Cork Modular: a Lightweight Temporary Housing

(Barreca 2022) proposed a **timber-cork** modular system (figure 2.3) intended for **lightweight temporary housing**, emphasizing **adaptability** and sustainability. The system utilizes a sequence of **modular timber portal frames**, constructed from spruce boards linked by hinges, facilitating the interchangeability of both structural elements and walls. This modular design allows for versatile configurations, catering to **diverse scenarios**.

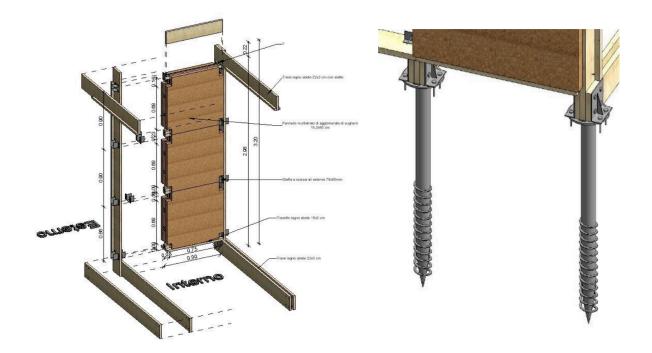


Figure 2.3: Structural design of the basic module, featuring (a) a shear wall and (b) screw foundations.

The structural system uses the platform frame concept, characterized by a lightweight load-bearing framework comprising solid timber uprights and crosspieces, mechanically

connected to the internal frame. This design prioritizes **ease of assembly** and **disassembly** while maintaining **structural integrity**.

Haiti's 5-Hour Emergency Shelter: an Open Source Interlocking Solution

Pieter Stoutjesdijk has designed an emergency shelter (figure 2.4) made from **digitally fabricated** components that can be **quickly assembled** in Haiti after the 2010 earthquake. This **cost-effective** design uses **interlocking pieces** (figure 2.5), requiring no additional materials, and can be easily manufactured and distributed. The design promotes **mass customization** and **personalization**. The shelter is adapted to Haiti's tropical climate with an undulating roof for shade and rainwater collection, and large ceilings and windows for ventilation.



Figure 2.4: Haiti's 5-Hour Emergency Shelter, an emergency shelter that assembles in 5 hours

Each component of the shelter features custom joinery, ensuring a precise fit with adjacent pieces. This interlocking design extends to the framework, flooring, roof, and walls, allowing for seamless assembly without additional fasteners (Azzarello 2013).



Figure 2.5: Haiti's 5-Hour Emergency Shelter, each section has a different kind of interlocking part

Table 2.1 outlines the design and optimization objectives identified in the reviewed timber shelters and structures. In addition to the examples mentioned above, other structures as well as Origami Cave by Lava Architects, Minami-Sanriku by Shoichi Haryu Architect & Associates, Pop-up Chapel, and Paper Log House by Shigeru Ban Architects are presented.

	Design and Optimisation Objectives								
Shelter/ Structure	Ease of Transport	Ease or speed of Assembly/ Manufacture	Structural Performance	Local Sourcing	Ease of Disassembly	Material/Cost Efficiency	Adaptability/ Personlisation	Climate-Resp onsiveness	
The Liina Shelter	*	*	*	*					
Glænø Stapel		*	*	*	*	*			
TimberCork Modular	*	*	*		*	*	*		
Haiti's Shelter	*	*				*	*	*	
Minami-Sanriku				*					
Origami Cave	*	*		*		*	*		
Pop-up chapel		*							
Paper Log House		*		*	*	*			

Table 2.1: Design and optimization objectives identified in the review of existing timber shelters and structures

This thesis focuses on a case study that explores **structural performance**, **material cost** and **efficiency**, and **local sourcing**. Other objectives, while valuable, are beyond the scope of this research and are recommended for future studies. The following section will discuss timber structures and their optimization methods.

Timber Structure

This chapter aims to address three sub-sections.

First, it examines the specific properties of timber and the limitations associated with it. Second, the chapter explores joinery structure, including its static and dynamic behavior. Finally, it investigates the process of Computer Numerical Control (CNC) on timber shelter production and design. Based on the findings of this section, the respective structural, material, and geometric properties for modeling the case study will be defined.

Timber Properties

"Out of all the natural materials wood has the most balanced characteristics and can be relatively easily worked (Binding, 1975)."

Wood is composed of cellulose and lignin, as shown in (figure 2.6). The cellulose fibers, which are long, provide strength along the grain of the wood, whereas lignin acts as a binder for these fibers, offering shear strength and facilitating the transfer of loads between fibers that are not continuous. In this structure, fiber represents the most robust component (McMullin 2017).

Timber is anisotropic, meaning that it exhibits varying material properties depending on its direction. The properties are strongest along the grain and weakest when measured perpendicular to it. Additionally, timber strength varies significantly by species, which can substantially impact the structural design and calculations. The anisotropic property of timber is dealt with by focusing on the direction of the load(Paul and Jonathan 2017). Timber shows ductile properties when compressed and brittle characteristics under tension and shear, with both failure modes potentially occurring at the same time (van de Kuilen and Sandhaas 2013).

Timber materials are made up of either sawn lumber or engineered (manufactured) wood products. Engineered lumber encompasses materials such as glued laminated timber, structural composite lumber, l-joists, and structural panels (McMullin 2017).

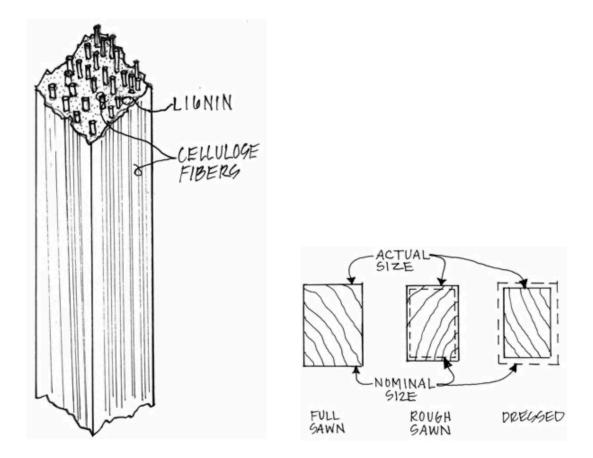


Figure 2.6: a) Conceptual Drawing of timber b) Type of Solid Sawn Lumber

General limitations of timber and Discontinuities

Despite the numerous merits of timber as a building material, it's essential to acknowledge certain structural limitations it poses (Voulpiotis, Köhler et al. 2021). Being a biological material, timber can have considerable defects and physical variations, and is susceptible to disease, infestation, and decay. This limits the predictability of the mechanical behavior of timber, which leads to justifications for the absence of design guidelines specifically related to wood-wood joints. The primary challenges faced by joinery structures include moisture sensitivity, natural defects, fire vulnerability, degradation of connections, and a lack of design guidelines (van Nimwegen and Latteur 2023). All construction materials exhibit some form of imperfections. In the case of timber, typical irregularities include knots, splits, checks, and shakes, as illustrated in

figure 2.7. These irregularities are not considered defects but rather discontinuities. The reference design values for timber already consider these characteristics. For instance, heavy timber beams often contain large discontinuities but still maintain substantial overall strength (McMullin 2017).



Figure 2.7: Natural Imperfections of Wood

The stress-strain curve in timber differs based on the type of load and the direction of the load relative to the wood's grain. For bending loads, the stress - strain curve is linear up to the proportional limit, beyond which strain increases at a faster rate than stress until the point of failure, as illustrated in (figure 2.8). In tension along the wood fibers, stress and strain increase linearly until approximately strain of 0.5 to1 percent, followed by sudden failure typically before reaching 2 percent strain, with minimal nonlinear behavior shown in (figure 2.8). Under compression parallel to the grain, stress and strain grow linearly to around strain of 0.5 to 1%, reaching a proportional limit Comparable to the yielding seen in steel, with compression strength gradually decreasing as strain increases, as depicted in (figure 2.8). Compression perpendicular to the grain initially shows a linear increase and then stabilizes at its ultimate capacity without further degradation, as the wood densifies, as shown in Figure x. While timber design generally remains within the linear section of these stress-strain curves, understanding the full curves is useful for gauging potential reserve capacity (McMullin 2017).

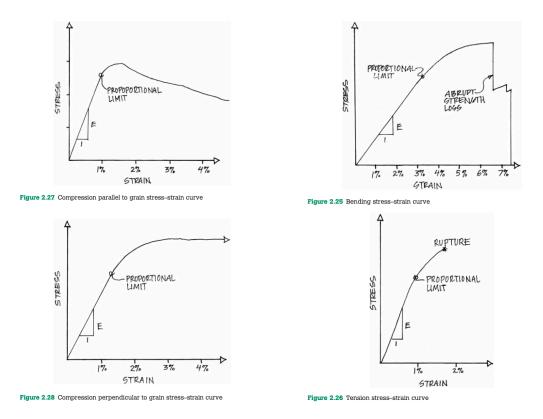


Figure 2.8: Stress - Strain Curve in Timber in Different Loading Conditions

Timber materials are made up of either sawn lumber or engineered (manufactured) wood products. Solid sawn lumber is produced by milling harvested trees, while engineered wood consists of smaller pieces of wood bonded together with adhesive. Sawn lumber is available in three size categories: full or rough sawn, and dressed, as depicted in (Figure 2.6) Dressed lumber, which is the most commonly used type, is typically what you would purchase at a lumber yard. Engineered wood products offer significantly enhanced strength and stiffness, contributing to the sustainability of timber by enabling the construction of longer spans and taller structures. These products include GLT, structural composite lumber , I-beams, and structural panels, as illustrated in figure. (McMullin 2017).

Timber Systems

The Common timber structure systems can be categorized as (Kolb 2008; McMullin 2017):

- log construction
- Timber-frame construction
- Light bearing wall: Balloon and platform frame construction
- Panel construction
- Frame construction
- Solid timber construction

Although each of these systems offers unique benefits, this research utilizes timber frame construction as the structural focus for the case study.

Timber Frame

Timber framing has been in use for over two thousand years. Its development was gradual, as it depended on the availability of tools and the growing skill of laborers to carry out the work. Early timber frames were initially stabilized by burying posts in the ground, but this led to rapid decay. To prevent this, carpenters adapted the structures to stand on stone foundations, making the frames more rigid with diagonal bracing and stronger joinery.

In numerous timber-frame structures, the structural framework that bears the load is left exposed. These types of buildings are common in East Asia (van Nimwegen 2023) ,across Eastern and Central Europe, as well as in England, northern Germany, Denmark, the Netherlands. In colder climates, the timber frames are often arranged in a tight grid of rectangles and squares, with windows seamlessly integrated into this grid. Historically, timber-frame construction developed in areas where wood was scarce enough that it could not be used for solid log construction. This method also accommodates shorter hardwood components. Today, the traditional visible timber-frame is rarely used in new constructions. Modern building materials and methods have replaced the classical timber-frame setups, though carpenters are still familiar with traditional techniques like struts and angle braces. Timber-frame buildings, now typically with the timber hidden behind cladding. Advances in machine assembly and wood drying technologies have made timber-frame construction a viable economic choice. Connections in timber-frame construction, such as mortise and tenon and oblique dado joints, are less expensive than those made from preformed metal or steel, particularly as the closely placed timber members bear lower loads. The primary load in timber-frame buildings is transferred directly through the contact points between timber pieces (Kolb 2008). This conclusion shows that Lock n Load should preferably provide an environment that can facilitate the process of design and optimization, effectively integrating all three approaches: analytical, numerical, and experimental.

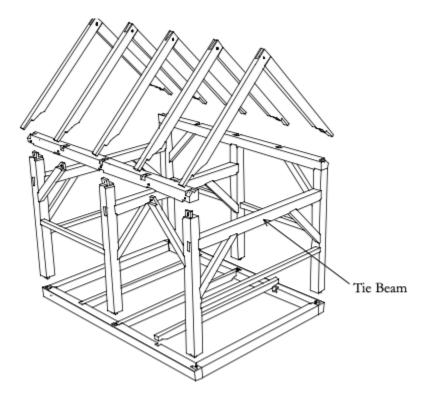


Figure 1-2 American Timber Frame (Redrawn from Sobon and Schroeder, 1984)

Figure 2.9: American Timber Frame

Timber frame walls are integral structural components that utilize a rigid framework of timber sections to transfer loads within both internal and external walls. The bottom plate, also known as the sole plate or sill, forms the base of the timber-frame wall, securing it to the floor construction. It is typically laid on its broader side to optimize support. The placement of the bottom plate varies based on the floor type: resting continuously on concrete slabs or masonry

plinths, or at specific points on timber joist floors. Studs, the principal vertical members of the wall, direct structural loads downwards to the foundation. These elements are essential for the framework, sometimes doubled to support greater loads or accompanied by cripple studs to reinforce openings. The spacing of studs typically ranges from 800 to 1200 mm, influenced by the architectural layout and structural requirements. Structural considerations for studs include potential buckling and bending due to lateral forces, with particular attention to the weakening effects at joint connections. Inclined bracing within the wall plane is essential for providing the necessary stiffness in timber-frame structures. These braces transfer horizontal forces, like those from wind, from the top and bottom plates to the foundation. Braces are typically installed in pairs since they are only capable of handling compressive forces, functioning as struts. Rails provide lateral support to sheathing or cladding and are crucial in preventing stud buckling in taller walls. While generally non-structural, rails become necessary around door and window openings where they function as lintels and sills. The top plate and head binder align and stabilize the studs at the upper limits of the wall. The head binder additionally supports the load from upper floors and roof structures, distributing these forces to the studs below. This arrangement is critical for maintaining the integrity and stability of the wall. Timber-frame construction utilizes various joints and fasteners to enhance structural integrity. Halving joints are commonly employed at connections between bottom plates and head binders, while mortise and tenon joints are predominantly used for studs, braces, and rails. Modern construction often supplements traditional wooden pegs with nails, screws, and close-tolerance bolts (Kolb 2008).

Wood joining techniques in timber buildings are shaped by cultural and environmental factors. Joints serve not only a structural role, but also contribute significantly to the architectural expression and embody the conceptual aspects of the timber design (Hudert 2019). Wood construction typically requires joining numerous building components in various ways. Historically, construction methods such as mortise and tenon, dovetail, dowel, split ring, and shear plate joints were employed to connect wooden components. Modern connectors now include nails, bolts, lag screws, truss plates, timber rivets, and engineered metal plate connectors (McMullin 2017). Despite the advancements in connection technology, traditional joints remain effective and add a unique aesthetic to exposed wood projects (van Nimwegen 2023). This thesis primarily focuses on the **pegged mortise and tenon (PMT)** joinery

connection, utilized in the GO case study. This specific connection formed the basis for the development of the tool.

Manufacturing of Timber Structure with Computer Numerical Control Production

In Eastern tradition, a master builder oversaw material selection, construction, and joint design. Conversely, Western cultures developed a divide between design and execution, persisting today. The rise of industrial methods and power tools further marginalized traditional joinery in the West (Hudert 2019). The adaptation of CNC machines for wood required specialized software. Despite challenges, they've become popular due to advancements in technology. They fall into two categories: stationary machines, where the workpiece is secured, and run machines, where the machine positions the workpiece (Tannert 2008). CNC machining uses computers to control tools, which requires coded instructions and G-code is a software programming language used to control a CNC machine. G-code, or geometric code, provides CNC machines with location instructions in a 3D coordinate system (X, Y, Z), along with parameters like speed, angle, and feed rate. M-code, short for machine code, handles non-movement functions, such as program termination. Together, they form the language of CNC machining (Roschlia 2023).

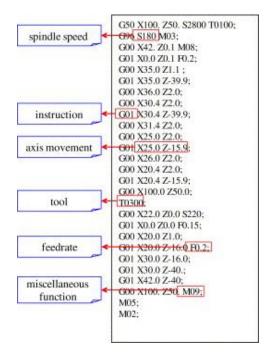


Figure 2.10: Elements in the G-code control formats

However, CNC machines can be programmed using methods beyond G-code, such as STEP-NC, which offers a more integrated and feature-based approach, but G-code remains the dominant language (Shin 2007). In CNC manufacturing, the general sequence is to design a part in CAD software, generate toolpaths and machining instructions in CAM software, and finally, output those instructions as G-code that controls the CNC machine (Lati 2021).

Timber Structure Optimization

Structural optimization involves designing material assemblies to sustain loads in the most effective manner. The goal is to determine the optimal structure that meets specified performance criteria, such as minimal weight, maximum stiffness, or enhanced resistance to buckling. This process necessitates clear definitions of "best" based on the objectives of the structure. Optimization must operate under various constraints, including limits on material quantities, allowable stresses, permissible displacements, and specific geometric configurations, to provide a viable and well-defined solution (Christensen 2008).

The design process should incorporates structural optimization and broader criteria into several main stages:

- 1. **Function**: Identifies the purpose and essential requirements of the product.
- 2. **Conceptual Design**: Determines the basic construction type, such as choosing between truss, suspension, or arch designs for a bridge.
- 3. **Optimization**: Refines the design within the defined constraints to enhance performance, often focusing on the efficiency of material use.
- 4. Details: Addresses market, social, and aesthetic considerations.

These steps ensure that the final product is not only structurally effective but also functional, economically viable, and aesthetically suitable. The traditional approach to the optimization step in design is iterative and intuitive. It involves proposing a design, assessing its compliance with requirements, and revising it as necessary. If a design fails to meet specifications like stress levels or is suboptimal (e.g., too heavy), it is revised and reassessed in a continual loop. This iterative process often employs computer-based methods such as the Finite Element Method (FEM) or Multi-Body Dynamics (MBD) to improve the accuracy and efficiency of design

evaluations. However, these methods do not fundamentally change the iterative nature of the process. In contrast, mathematical design optimization takes a systematic approach by formulating a specific mathematical problem where design requirements are constraints, making the process more automatic and less reliant on iterative revisions (Christensen 2008; Haftka 2012).

Structural optimization problems might appear straightforward to set up but can involve complex elements. They are typically presented as:

Determine the vector χ to minimize the function $f(\chi)$, while ensuring that $g(\chi)$ does not exceed zero.

Here, $f(\chi)$ represents the scalar objective function, χ is a vector with *n* components, and $g(\chi)$ comprises *m* constraint components. Such challenges are known as mathematical programming problems. The formulation simplifies in common presentations to:

minimize $f(\chi)$ such that $g(\chi) \le 0$

or more succinctly:

minimize $f(\chi) | g(\chi) \le 0$

This representation means that each element of the vector $g(\chi)$ must individually satisfy the condition ≤ 0 . Although the notation may vary, the underlying principle remains that minimizing $f(\chi)$ is equivalent to maximizing -f, and $g(\chi) \leq 0$ corresponds to $-g(\chi) \geq 0$. This equivalence is crucial in formulating optimization problems effectively.

Structural optimization problems can be categorized into three main types (figure x) based on the geometric aspects they address: **size**, **shape**, and **topology** optimization.

Size optimization focuses on scenarios where the overall layout of the structure is predefined, but the dimensions of specific components are not fixed figure x.

Shape optimization deals with optimizing the specific contours or forms within a given domain figure x.

Topology optimization extends to determining the number and configuration of voids within a domain, as well as how these voids connect. This form of optimization offers extensive freedom in modifying the structure's topology to meet specific criteria and objectives (Bendsøe 2004; Querin 2017).

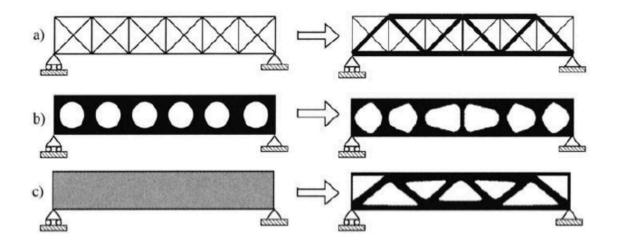


Figure 2.11: a: Size, b: Shape, c: Topology optimization

Various methods and tools are utilized for structural optimizations, with the most commonly employed being Linear Programming, Sequential Linear Programming, Genetic Algorithms, Newton's Method, the Lagrange Multiplier Rule, and Gradient-Based Optimization(Bendsøe 2004; Banichuk 2010).

Literature Review: Analysis, Simulation, and Optimization of Timber Structures

One of the earliest attempts to optimize timber frame structures was made by (Topping1984), who introduced the use of **sequential linear programming** for this purpose. In their study, the design variables include **member cross-sectional properties** and **joint coordinates**, with the objective of **minimizing weight**. (Stanić 2016) presented an **cost optimization** of cross-laminated timber plates with stiffening ribs using enhanced assumed strain **FEM**. This method avoids shear locking in thin plates and meets **Eurocode 5 constraints** on **deflections**, **stresses**, and **eigenfrequency**. **Gradient optimization** yields a cost-efficient timber plate design, demonstrated with numerical examples.

(Pech 2019) developed a new optimization method that considers mechanical property

distributions and stress states in wooden boards. After reconstructing knots and determining stiffness, beams are analyzed with an **FEM** to find optimal configurations. To handle complexity, **metaheuristic algorithms** and a **performance-approximating** metamodel were used, **reducing maximum deflection** by **15%–20%** compared to traditional GLT beam production.

(JELUŠIČ 2018) introduced an optimal design approach for timber beams with non-uniform cross-sections using **multiparametric mixed-integer nonlinear programming (MINLP)** along with **response surface optimization (RSO)**. The optimization model incorporates Eurocode specifications and uses FEM to evaluate design performance based on input parameters which contains the **cost objective function**.

(Kravanja 2021) optimized a one-story timber structure with glued laminated timber frames and steel purlins, rails, and façade columns using mixed-integer nonlinear programming. The objective was to **minimize** the **cost of material** while adhering to **Eurocode** standards. The Modified **Outer-Approximation/Equality-Relaxation algorithm** and a **multi-level strategy** were used, resulting in optimal material use and frame configuration.

Some studies specifically concentrate on enhancing timber connections. The design of timber structures heavily relies on the performance of the joints. Joint strength is a key determinant of overall structural strength, while joint stiffness affects the structure's deformation. Furthermore, the size of timber members is often chosen based on the characteristics of the connectors used in the joints (Leichti 2000). The analysis of timber connections is typically done using analytical, experimental, or numerical methods (Fang 2020). Table 2.2 presents the detailing objectives, key findings, and optimization parameters for different types of joints, which were examined through numerical, experimental, and analytical analyses.

Nearly all of the studies summarized in Table 2.2, which performed physical test validations, demonstrated trends consistent with their numerical and analytical simulations. Additionally, various types of loading conditions are presented in this literature review. This diversity ensures that the numerical FEA and analytical models can provide reasonable estimates that are consistent with actual testing under different loading conditions.

	Type of Joint	Objective(s)	Analyzing Method	Optimization parameters	Key Findings
(Hu and Chen 2021)	MT joints	1.Withdrawal load capacity (WRL) 2.Bending load capacity (BLC)	1.FEM) with response surface method 2.Experim ental	1 Tenon length(L) 2. Tenon width (W) 3. Tenon thickness(T)	 L has a greater effect on WRL followed by W. T has a greater effect on BLC followed by L. (w < I < 2w) ratio is recommended
(Eckelman, Erdil et al. 2006)	MT joints	Bending moment capacities (BMC)	Experime nt with specimen s	1.Diameter(D) 2. Distance from longitudinal axis of tenon to lower edge of stretcher (W), Fs, Fns = BMC 3. Keeping or removing shoulders	 Close-fitting shoulders greatly increase the strength of the joints The formulas below are obtained: <i>Fs</i> = 0.934×^{2w}/_{D1.66}×<i>Fns</i> When shoulders are contributed, and T is withdrawal strength of the T in tension <i>FS</i> = 0.894 × <i>w</i> × <i>T</i>
(Wielinga 2023)	Dovetail, arrow and yin yang joints	Yield Strength in tension, shear, compression	FEM (Linear Elastic)	 Total width wt [mm] Width dovetail head w1 [mm] Width dovetail neck w2 [mm] Total height ht [mm] Height dovetail h1 [mm] Filet radius fr1 [mm] Dovetail angle a 	 The contact area has a large impact on the strength of the connection for both tension and shear. The dovetail was optimal in both tension and shear. The dovetail under tension has the most optimal force path A larger width and filet radii lead to higher shear capacity of the dovetail and arrow joint. The yin yang performed the worst under both tension and shear
(Kasal, Smardzewski et al. 2016)	MT joint	 Stiffness Moment Capacity 	FEM (Nonlinear orthotropi c)	 Tenon length(L) Tenon width (W) Tenon thickness(T) 	 Tenon width increases joint stiffness Tenon length boosts moment resistance. Optimal sizes identified for L /T-shaped joints.

Table 2.2: Review of Geometrical optimization of timber Joinery studies with different methods of analysis:Parameters ,Methodologies and Key Findings

(Kaijima, Xuereb Conti et al. 2016)	Topologically Interlocking Joineries	Stiffness	FEM (Orthotrop ic)	 Height (HT) Width at the bottom (WB) 	 Adjusting HT and WB significantly improves its stiffness HT has a higher impact on the stiffness
(Kaijima, Xuereb Conti et al. 2015)	Basara Splice and Shihou-Ari Splice	Stiffness in pulling out tension, bending, and self-weight	FEM (Orthotrop ic)	1.Dovetail angle 2. Dovetail position	 Dovetail angle for Basara and dovetail position for Shihou-Ari were identified as influential in joint stiffness. Increasing surface friction might be more critical than geometric parameters in improving the stiffness
(Láng and Fodor 2007)	Notched cross-halved joints	Stiffness	FEM (Anisotro pic)	1. Gap distance 2. Contacting domain	Configuration of the joint provides added lateral stiffness and stability, which could be beneficial in structures under dynamic loads
(Wilczyński and Warmbier 2003)	MT joints	 Bending strength Stiffness 	Analytical (regressio n functions)	 Tenon length(L) Tenon width (W) Tenon thickness(T) 	 The bending strength and stiffness rise as the tenon size increases. The tenon (L) has the greatest impact on joint strength, while the influence of tenon (W) is less significant, and the effect of tenon (T) is minimal. The joint stiffness primarily depends on the tenon (W), with the effects of tenon (L) and (T) being less significant.
(Moradei, Brütting et al. 2018)	Traditional Japanese and Chinese interlocking timber joints	1.Structural Capacity 2. Stiffness	FEM	Cross-sectional Properties	The study highlighted the direct correlation between the geometry of the joint's cross-section with the capacity and stiffness of the member.
(Guan, Kitamori et al. 2008)	Nuki joint	Local failure	1. FEM (nonlinear) 2. Experime ntal validation	wedge size	In cases where wedges are too large, the resulting contact stresses on the column can surpass the timber's critical stress limit, potentially causing localized damage to the column.

Chapter Conclusion and Discussion

The review of existing timber shelters reveals a range of optimization objectives. The most frequently observed objective was ease of assembly, manufacturing, and in some cases, disassembly. Working with available resources or tools, material and cost efficiency were also common objectives. Structural Performance is a crucial goal in designing shelters intended for relatively longer duration of use. In addition, Adaptability, Customization, and Climate-Responsiveness were also mentioned as design objectives in some cases.

Understanding the design objectives for emergency timber shelters reveals the key areas where Lock n Load can provide support to designers. **To maintain a manageable research scope, Lock n Load will prioritize structural performance, material cost-efficiency, and local sourcing.**

• The review also underscored the significant role of **geometry optimization** in enhancing the **structural performance** of timber structure and connections.

Consequently, the main variables in the case study were chosen from geometrical variables. This also leads to the conclusion that "Lock n Load" should be able to support **geometrical input** and **output**.

- To ensure accurate structural design in an automated process, "Lock n Load" requires a comprehensive material library encompassing the diverse properties of different timber types. This includes not only mechanical properties but also crucial factors like grading, moisture content, and other relevant characteristics. By incorporating this detailed information, designers using "Lock n Load" can effectively differentiate between various qualities of timber within the same species, enabling more informed and precise design choices. The case study should define what properties are critical and necessary.
- It was observed that **analytical**, **numerical**, and **experimental** methods all demonstrated effectiveness in optimizing timber elements.

This conclusion shows that Lock n Load should preferably provide an environment that can facilitate the process of design and optimization, effectively integrating all three approaches: analytical, numerical, and experimental.

In the review of optimization studies focused on global structural performance, the primary objectives were typically weight, cost minimization and material efficiency. While structural performance often served as a constraint in these optimizations, there were also instances where it was the central objective itself.

Based on this finding, in the case study, weight optimization was adopted as the primary objective function for optimizing the frame structure.

- However, in the optimization of joints, as their nature dictates, the primary objective in all cases was to enhance structural performance, such as strength, stiffness, ductility, and energy dissipation, through iterative modifications of geometry variables.
 Consequently, in the case study, the primary objective of the optimization process was to enhance the load-bearing capacity of the joints.
- The review of simulation and optimization of timber joints highlighted the complexities inherent in designing with wood, particularly in the area of **material modeling**. Additionally, many numerical lead simulation studies in the literature have demonstrated the critical importance of selecting appropriate material models to achieve more realistic simulations.

In the modeling of the joints in the case study, this conclusion led to special attention being given to the material model for refining and validating the simulation results.

- Most of the literature studies on optimizing joints and timber structures focus on common joints and elements used in **Timber Frame** systems. Therefore, a timber frame can be a good option for a case study, as the existing literature can provide methods and insights for design and optimization.
- To facilitate the automated transition from timber shelter design to CNC fabrication,
 "Lock n Load" must have the capability to convert design outputs into G-code, the

programming language used by CNC machines. The case study should explore how this conversion is achieved.

These findings informed the definition and design of the case study's objectives and the chosen methods for design and optimization.

"By applying appropriate tools and techniques to a good piece of timber, a woodworker's imagination is limited only by the nature of his material- a material that often seems to have a life of its own"

Norwegian Wood: Tradition of Building, Jerri Holan

Case Study

A case study focusing on timber frame construction was conducted to further investigate design and optimization methods for timber structures. Timber frame was selected due to its long history of use and widespread familiarity in many regions globally. Additionally, there exists a substantial body of literature on timber frame design, optimization, and construction, making it a suitable system for a case study aimed at establishing a digital framework for **automation** of design and optimization.

Preliminary Design

The initial step in designing the timber frame involved defining the building's footprint. To facilitate transportation and assembly, a maximum element length of 2 meters was established. Three columns in a row were positioned along both lengths of the building, resulting in a 4 by 2 meter timber frame shelter (figure 3.1).

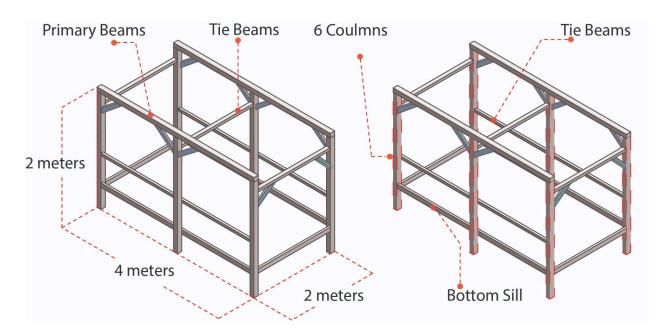


Figure 3.1: Footprint and Overall Shape of the Shelter

The columns serve to support two primary beams that span the length of the building. It's important to note that this represents just one specific configuration for a timber frame system. While this example demonstrates support from two sides, alternative designs exist where the frame could be supported from four sides or other variations, depending on the structural requirements and architectural intent.

Design and Optimization of Timber Frame

This research designs the structure of the timber frame according to Eurocode 5 (EN 1995-1-1), with a focus on optimizing member cross-sectional properties (figure 3.2). The primary goal of the optimization was to reduce the weight of the frames. A Python script was created to

perform the iterations, which can be found in the appendix. In this stage, the structure was assumed to be completely rigid.

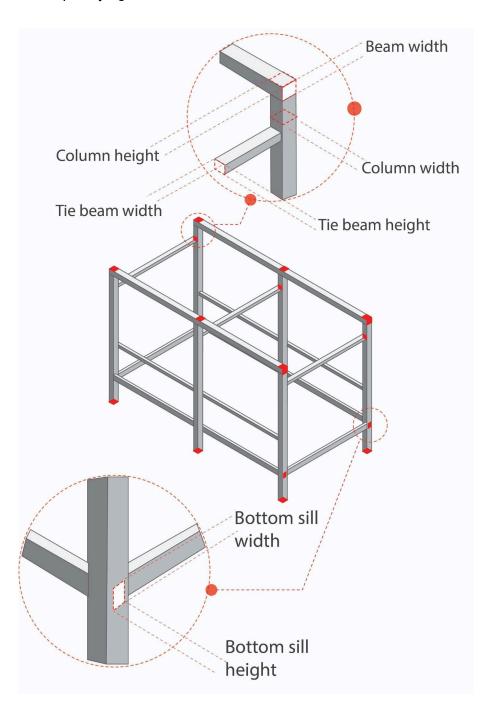


Figure 3.2: Cross-sectional Variables in Optimisation of the Timber Frame

The same cross-sectional properties are used in each iteration for the columns and beams in the frame. For practical purposes, the length of both the columns and beams in the frame has been set to a constant value of 2 meters. The governing load combinations for both ULS and SLS (respectively Equation 3.1, and 3.2) were assumed based on the most demanding load scenarios recommended in (EN 1990 6.4.3.2) for a shelter in the Green Village in Delft, the Netherlands. The more detailed load calculation can be found in the appendix. In this study, weight is used as the primary objective function to simplify the design problem while optimizing timber frames. This simplification helps in formulating the algorithm. The design variables include modifications to the members' cross-sectional dimensions, width (w) and thickness (t). The objective function is subject to both equality and inequality design and dimensioning constraints. In the objective function, C represents the weight of the material, and ρ denotes the density of the timber as detailed in Equation 3.3.

$$\sum_{j\geq 1} \gamma G.j. Gk.j + \gamma Q.1. Qk.1 + \sum_{j\geq 1} \gamma Q.i. \psi 0.i. Qk.1 \qquad Equation 3.1: ULS Load Combination$$

$$\sum_{j\geq 1} Gk.j + Qk.1 + \sum_{j\geq 1} \psi 0.i. Qk.i \qquad Equation 3.2: SLS Load Combination$$

$$C = (t.w).\rho \qquad Equation 3.3$$

The dimensioning equations for the timber frame are established based on formulas from the Eurocode. For Ultimate Limit State (ULS) considerations, these equations account for the cross-sectional resistances of columns and beams under axial compression force, bending moment, shear force, and buckling. Additionally, for Serviceability Limit State (SLS) considerations, the equations address the deflections of the beam.

In this design approach, the **compressive stress** for the column $(\sigma_{c,o,d})$ in the timber's rectangular cross-sections must not exceed the design compressive strength $(f_{c,o,d})$, as outlined in Equations 3.4 and 3.5. Specifically, Equation calculates $\sigma_{c,o,d}$ where N_{ED} is the design axial compressive force and A is the cross-sectional area. The modification factor k_{mod} adjusts for

the impact of load duration and moisture content. The term $(f_{c,og})$ refers to the characteristic compressive strength of timber, and y_{M} is a partial factor accounting for the material properties.

$$\sigma_{c,o,d} \leq f_{c,o,d}$$
 Equation 3.4

$$\frac{N_{ED}}{A} \le k_{mod} \cdot \frac{f_{c,o,d}}{y_{M}}$$
 Equation 3.5

The **bending stress** about the y-axis ($\sigma_{m,y,d}$), in the beam should not exceed the design bending strength ($f_{m,y,d}$) as specified in Equations 3.6 and 3.7. In these formulas, ($M_{y,ED}$) represents the bending moment around the y-axis, w_y denotes the section modulus about the y-axis, and $f_{m,g,k}$ is the characteristic bending strength of the swan timber.

$$\sigma_{m,y,d} \leq f_{m,y,d}$$
 Equation 3.6

$$\frac{M_{y,ED}}{w_{y}} \le K_{mod} \cdot \frac{f_{m,g,k}}{y_{M}}$$
 Equation 3.7

The design **shear stress** for the beam, $\tau_{d'}$ must be less than or equal to the design shear strength, $f_{v,d}$ as outlined in Equations 3.8 and 3.9. In these equations, v_{ED} is the design shear force, while b and h represent the width and height (depth) of the cross-section, respectively. The term $f_{v,g,k}$ refers to the characteristic shear strength of timber, and k_{cr} is a factor that accounts for the potential cracking of the timber.

$$\tau_d \leq f_{v,d}$$
 Equation 3.8

 $\frac{3}{2} \cdot \frac{v_{ED}}{b_{ef,h}} \le k_{mod} \cdot \frac{f_{v,g,k}}{y_{M}}$ Equation 3.9

$$b_{ef} = k_{cr} \cdot b$$
 Equation 3.10

Columns of the timber frame are evaluated for **compressive** and **buckling resistance**. This assessment occurs in two contexts: for buckling about the y-axis, which is within the plane of

the frame, and for buckling about the z-axis. These checks are detailed in the respective equations 3.11 to 3.16 provided in the documentation.

$$\begin{split} \sigma_{c,o,d} &\leq k_c \cdot f_{c,o,d} & Equation 3.11 \\ \frac{N_{ED}}{A} &\leq k_c \cdot k_{mod} \cdot \frac{f_{c,o,g,k}}{y_M} & Equation 3.12 \\ k_c &= \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^2}} & Equation 3.13 \\ k &= 0.5. \left[1 + \beta_c (\lambda_{rel} - 0.3) + \lambda_{rel}^2\right] & Equation 3.14 \\ \lambda_{rel} &= \frac{\lambda}{\pi} \cdot \sqrt{\frac{f_{c,o,g,k}}{E_{o,g,05}}} & Equation 3.15 \\ \lambda &= \frac{L_{ef}}{i} & Equation 3.16 \end{split}$$

For SLS design in timber framing, various deformations of the beam are considered:

- w_c is the precamber.
- w_{inst} is the instantaneous deformation.
- w_{creep} is the creep deformation.
- w_{fin} is the final deformation: $w_{inst} + w_{creep}$.
- $w_{net.fin}$ is the net final deformation: $w_{inst} + w_{creep} w_c$.

According to EN 1995-1-1, for a fixed beam, there are recommended limits for these deformations. These limits specify the maximum allowable deformations that should not be exceeded to ensure the structural integrity and functionality of the beam over time.

w _{inst}	W _{net.fin}	W _{fin}
L/300 to L/500	L/250 to L/350	L/150 to L/300

Creep, or the gradual deformation of a material under constant stress, is another consideration when designing timber structures. Eurocode 5 provides a framework to account for this time-dependent behavior.

The additional deformation caused by the permanent weight of the structure (dead load) is calculated as:

$$w_{creep,g} = w_{inst,g} \cdot k_{def}$$
 Equation 3.16

For leading variable action the creep deformation is:

$$w_{creep,lead} = w_{inst,lead} \cdot k_{def} \cdot \psi_{Lead}$$
 Equation 3.17

For accompany variable action, the calculation is similar:

$$w_{creep,acmp} = w_{inst,acmp} \cdot k_{def} \cdot \psi_{acmp}$$
 Equation 3.18

Finally the final deformation is calculated by :

$$w_{fin} = w_{inst} + w_{creep,g} + w_{creep,lead} + w_{creep,acmp}$$
 Equation 3.19

The results of frame cross-sectional optimisation

Three predominant wood species commonly found in the Netherlands and other parts of Western Europe were utilized in the optimization and design process: **DouglasFir, European Spruce, European Larch**. Table 3.1 shows the material properties of three species used in the cross-sectional optimization. The timber elements were optimized by iterating through a range of cross-sectional dimensions, with widths of 95, 100, 115, 125, 138, 150, and 175 mm, and thicknesses of 100, 110, 115, 120, 125, 130, 135, 140, 145, 150, 155, 160, and 165 mm.

	Douglas fir	European spruce	European Larch
y _M	1.3	1.3	1.3
ρ (Kg/m3)	550	440	610
$\mathbf{f}_{m,g,k}$ (N/mm3)	86	63	91
${f f}_{v,g,k}$ (N/mm3)	8.2	5.3	9
$\mathbf{f}_{c,o,d}$ (N/mm3)	42	35	45
Е (kN/mm3)	12.17	9.7	11.2

Table 3.1: Material Properties of three species used in the Cross-Sectional Optimisation

The results (Figure 3.3, 3.4, 3.5, appendix) indicates that for most "Unacceptable" cross sections, the Serviceability Limit State (SLS) was governing failure criteria, indicating that deflections exceeded allowable limits, potentially leading to serviceability issues such as excessive sagging. Bending utilization emerged as another critical factor leading to design failure, also marked as "Unacceptable." This indicates that the selected sections were insufficient to bear the applied loads, necessitating resizing or reinforcement. Both factors were optimized by increasing the beam's thickness. As the beam and column thicknesses were kept equal in each iteration, the column never reached its failure point and, therefore, did not govern the structure's dimensions. The similarity in cross-sectional dimensions for columns and beams reduces the likelihood of buckling or compression strength surpassing acceptable limits. Table 3.2 presents the most optimal cross-sections in terms of weight that meet the structural requirements outlined in Eurocode 5. While Larch was stronger, Douglas Fir offered comparable strength with smaller dimensions, due to its lower density and resulting lighter weight, which reduced the overall load on the shelter. Spruce, although requiring a slightly larger cross-section, still maintained a lower weight due to its lower density compared to the other two options.

Species	Weight (kg)	Width (mm)	Thickness (mm)	Bending Utilisation (%)	Shear Utilisation (%)	SLS Utilisation (%)	Compress ion Utilisation (%)	Buckling Utilisation Y (%)	Buckling Utilisation Z (%)	Final Utilisation factor (%)
DouglasFir ¹	12.54	95	120	37.94%	23.88%	97.23%	4.18%	5.10%	7.22%	97.23%
Spruce ²	10.87	95	130	44.13%	34.10%	95.95%	4.63%	5.28%	8.29%	95.95%
Larch ³	14.49	95	125	33.05%	20.88%	93.47%	3.75%	4.79%	7.35%	93.47%

Table 3.2: The Optimal Dimensions and their Corresponding Utilization Factors and Weight

As illustrated in (Figure 3.3, 3.4, 3.5, appendix), varying the width-to-thickness ratio of timber elements can greatly enhance the structural performance of timber frame components. Therefore, identifying the optimal width-to-thickness ratio could be a valuable area for further optimization. The cross sections mentioned in the table 3.2 will be utilized in the next chapter to design the optimal timber joints.

¹ Pseudotsuga Menziesii

² European or Norway Spruce (Picea abies)

³ European Larch (Picea abies)

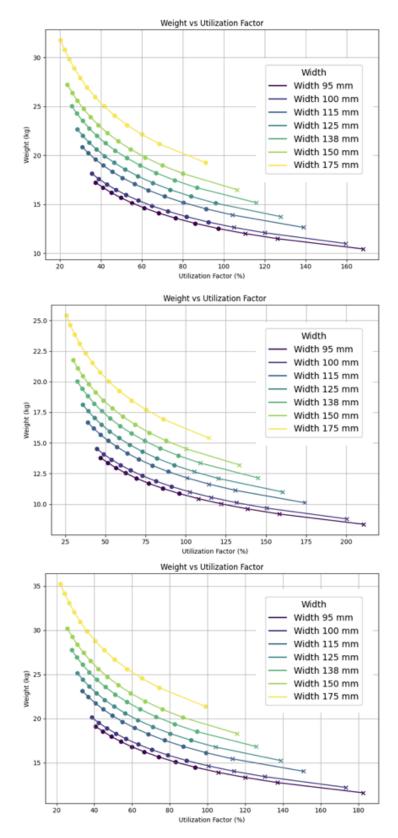


Figure 3.3: Weight to Utilization Factor, from top to bottom, Douglas Fir, Spruce, Larch

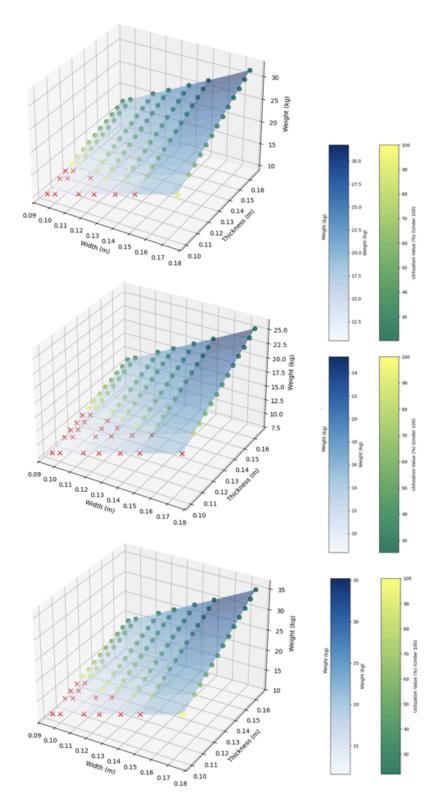


Figure 3.4: Dimensions, Weight, Utilization Factor, from top to bottom, Douglas Fir, Spruce, Larch

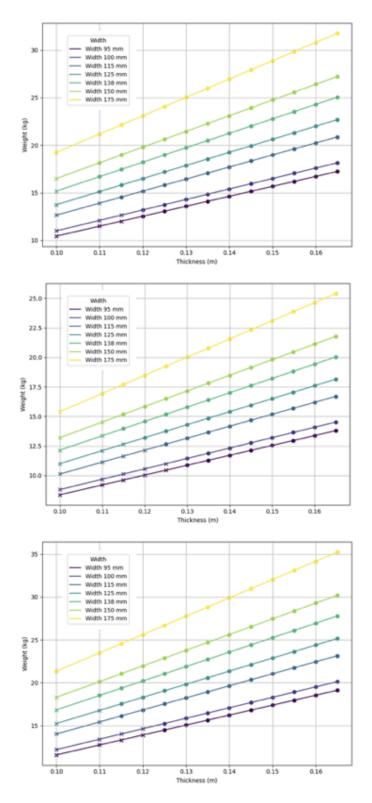


Figure 3.5: Dimensions, Weight, Unacceptable Utilization is shown by cross mark, from top to bottom, Douglas Fir, Spruce, Larch

Design and Optimization of the connections

Timber framing involves the use of large, widely spaced timbers that are connected with all-wood joints. In timber frame design in order to withstand Unprecedented events, such as seismic events, ductility is a key factor in determining performance. This is especially true for the connections within the frame. Ductility allows a structure to exhibit nonlinear behavior, preventing sudden failures. In timber frames, ductile joints enable the structure to yield without collapsing, redistributing forces within the frame to enhance its resilience during such events (Schmidt 1999; Schmidt and Miller 2004). The timber frame system analyzed in this case study required four types of joints: **Pegged Mortise and Tenon joints**, **Scarf joints**, **Gooseneck joints**, and blind mortise and tenon joints (Figure 3.6). Two of these joint types (Pegged Mortise and Tenon and Scarf Joint) were optimized.

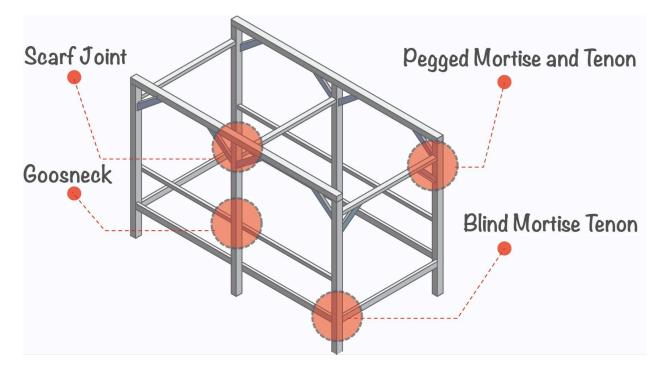


Figure 3.6: The Position and type of Joints in the timber structure

Pegged Mortise and Tenon (PMT)

The PMT method is one of the oldest construction techniques, dating back to ancient times (Benson 1997). In timber-frame construction, pegs secure the tenon inside the mortise which provides a semi-rigid connection between frame members. A common use of the mortise and

tenon connection is to join a beam to a post in a heavy timber structure, (as shown in figure 3.7) (Schmidt 1997).

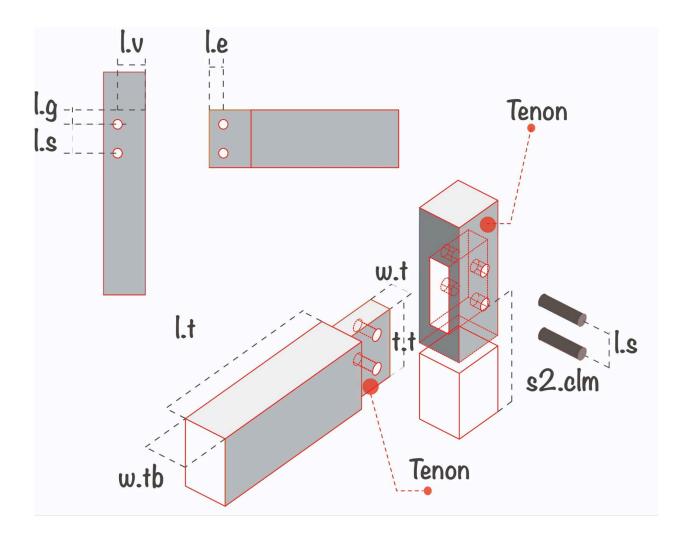


Figure 3.7: A drawing of Pegged Mortise and Tenon with Dimensional Details

Standard mortise and tenon joints are capable of effectively transmitting shear and compressive forces from the beam to the post through direct wood-to-wood contact. However, under wind loads or other similar conditions, the joint may be subjected to tensile forces that try to pull the tenon out of the mortise. In such cases, the connection forces must be transferred between the mortise and tenon using wooden pegs (Schmidt and Miller 2004). Peg sizes and wood species are similar between the United States, United Kingdom, and Asian timber framing

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practices. However, in Japan, square pegs are more commonly used instead of round ones (Brown 1995). The overall strength of the connection depends on various factors, including the bending and shear strengths of the peg, as well as the dowel bearing strength of the peg within the frame (Schmidt 1999). Peg failure is the preferred failure mode due to the ductility it displayed before reaching ultimate failure. By prioritizing peg failures, joints can be repaired after extreme loading events simply by replacing the damaged pegs (Schmidt and Miller 2004).



Figure 3.8: A Pegged Mortise and Tenon joint connecting a Beam to a Post

K. W. Johansen proposed a yield model in 1949 to predict the capacity of symmetrical steel-dowelled timber connections, considering various potential failure modes such as bearing failure and dowel moment yielding. H. J. Larsen expanded this model in 1973 to include additional failure modes for single and double shear connections. This method forms the foundation of the NDS (AFPA, 1991), European Yield Model (EYM) and underpins design codes

such as (BS EN 1996-1 2004a) and (BS 5268 2002). However, steel-dowelled connections differ significantly from timber-pegged connections, making Johansen's bearing failure modes inapplicable to traditional timber joints. This is due to the similar bearing stiffness between the pegs and the connection material, as well as differences in the shear-to-bending stiffness ratio between timber pegs and steel dowels (Shanks, J. and P. Walker 2009). The analytical method for pegged mortise-and-tenon joints in (Schmidt and Mackay 1997) applies the European Yield Model, focusing on failure modes under tension load. MacKay tested typical U.S. carpentry connections and introduced additional yield modes specific to U.S. timber-pegged connections, which also account for tenon relish failure. (Schmidt and MacKay 1997) identified a third failure mode in joints. Two failures were mode Vd, and one was a single flexural hinge (IIIs), forming at the dowel's center due to localized crushing in the mortise member, allowing the dowel to rotate. The (Schmidt 1999)'s study found that Mode IV failure is not applicable to timber frame joints, and Mode IIIs, which happens in joints with thin side members like metallic plates, is unlikely in MT connections due to the significant localized crushing required in the mortise member. Their review identified five potential failure modes in traditional timber frame construction. Modes Im and Is are the two currently recognized in the NDS for timber frame joints. Three additional modes include peg bearing failure (mode Id), shear and bending failure (mode Vd) in pegs, and peg bending failure with a one flexural hinge. Mode Vd is mainly a shear failure, with fractures near ultimate loads caused by bending. Figure 3.9 illustrates five failure modes for timber frame joints under tension.

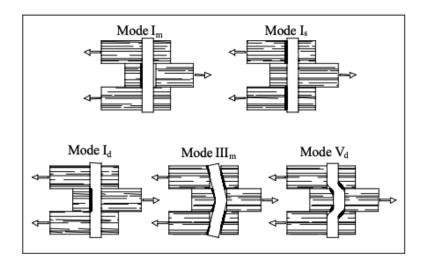


Figure 3.9: Proposed Failure Modes by Schmidt

(Shanks and Walker 2009) expanded the analytical model for pegged mortise-and-tenon tension joints by incorporating the elasto-plastic behavior and energy dissipation of the peg. However, Shanks' model did not incorporate the tenon relish failure mode introduced by Schmidt, as this failure mode has not been observed in tests on U.K. connections. The connection capacities proposed by U.S. research are not directly applicable to U.K., as U.S. timber joints are often made from wood with low bearing strength and use relatively stiff oak pegs.

Detailing Requirements and equation for PMT

The preferred failure mode in most design situations is the failure of the fastener, rather than the timber. The NDS outlines minimum detailing requirements to ensure this preference. Similarly, tests on MT joints with wooden dowels have shown that they can be ductile when proper spacing, end distance, and edge distance are maintained (Schmidt 1999). The goal of the minimum spacing requirements is to ensure localized failure of connection inside or around the fastener. This is favored over the failure of the base material, such as mortise splitting or tension failure in the tenon relish, which results in a sudden, brittle collapse, causing structural unserviceability and making repairs challenging. Previous tests (Kessel 1990; Kessel 1996; Schmidt 1997; Schmidt 1999; Schmidt and Miller 2004; Shanks and Walker 2009) have shown that peg failure can exhibit some ductility before losing load-carrying capacity. The minimum spacing requirements for pegged and bolted connections are determined by the joint configuration, bolt diameter, material breadth, and fastener aspect ratio, which impacts the connection's mechanics.

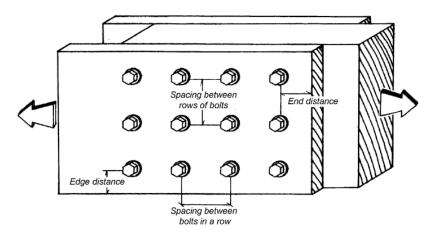


Figure 3.10: Drawing shows spacing dimensions around the bolts

In the absence of comprehensive guidelines for wood-wood connections in building codes, one viable approach for determining appropriate spacing and peg geometry involves employing the concept of an equivalent steel bolt. This method entails analyzing the wood connection by drawing parallels to a steel bolt connection. (Schmidt and MacKay 1997; Schmidt 1999) developed an analytical model (figure 3.11) for determining spacing requirements for timber frame joints using wooden pegs, based on the concept of an equivalent steel bolt. They reported that a comparison between experimental and analytical work demonstrates that specifying minimum end, edge, and spacing distance for pegs ensures that a brittle failure of the connected members will not happen before significant deformation of the joint after yield. However, the end and edge distances calculated with this equivalent steel bolt method tend to be more conservative compared to the minimum values observed in physical tests. The proposed design process is as follows: the designer first establishes the required load capacity for the joint. Then, the size and number of pegs needed to support this load are calculated using the five failure modes and a safety factor. The strength of a single peg is then substituted into the four EYM equations for double shear connections with a steel bolt. The largest diameter from the EYM equations is used as the equivalent steel bolt for the joint design (Equation 3.19). In pegged mortise and tenon joints, if the tenon plug experiences shear failure (also known as relish failure), the joint will fail suddenly and without warning. To prevent this type of brittle failure, it's crucial to maintain a minimum distance between the edge of the wood and the peg. This ensures that the surrounding wood material fails first, forming "yield hinges" in the pegs. This type of failure is more gradual and predictable, allowing the joint to deform before it completely break(Shanks, Chang et al. 2008)

Mode I_m

M-1-III

Mode Is

$$Z = \frac{D t_s F_{es}}{2K_{e}}$$

Mode III_s

$$Z = \frac{K_3 D \text{ is } F \text{ em}}{1.6 \text{ K}_{e}(2 + \text{ R}_{e})}$$
Mode IV

$$Z = \frac{D^2}{1.6 \text{ K}_{e}} \sqrt{\frac{2 \text{ Fem } F \text{ em}}{3(1 + \text{ R}_{e})}}$$

 $Z = \frac{D t_m F_{em}}{4 K_{\hat{e}}}$

Equation 3.19, Z represents capacity of Steel Bolt in tension and D is the diameter of the bolt

The capacity of a timber frame joint in double shear is determined by the lowest value among three different equations. This model categorizes bearing failure into three categories according to material strength under steel load. Two modes consider the strength of tenon and peg, while the third focuses on the mortise. Additionally, another mode is calculated by the shear span-to-diameter ratio of peg and mortise or tenon.

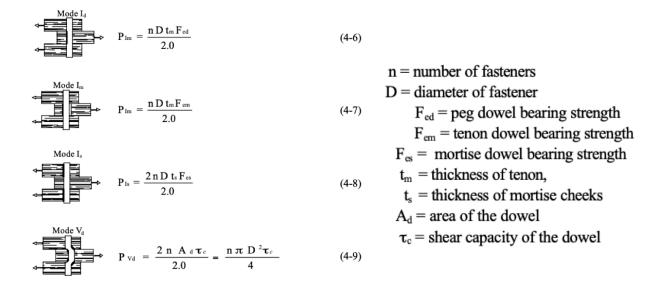
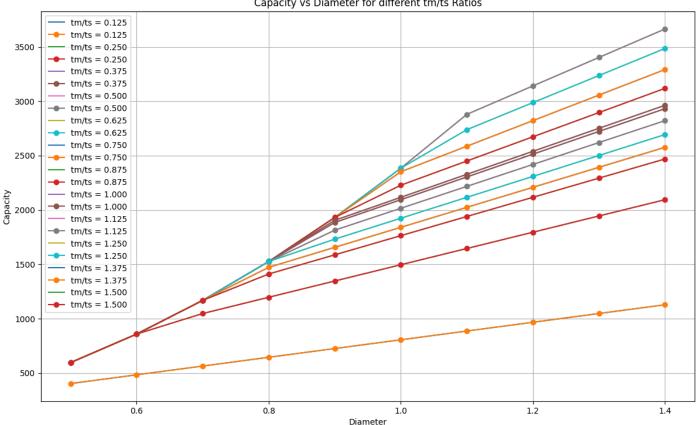


Figure 3.11: Equivalent Steel Bolt Method

Geometry Optimisation of PMT Joints Using Equivalent Steel Bolt Method

A Python script (Appendix), utilizing the equivalent steel bolt method, was developed to determine the peg diameter yielding the highest tension capacity while adhering to spacing constraints. The script generates edging, end, spacing, and perpendicular-to-grain edge distances, providing essential data for the spacing requirements and geometry configuration of a PMT joint. Spacing requirements for Douglas Fir timber were sourced from (Schmidt 1999). However, due to the absence of a specific factor for edge distance perpendicular to the grain, the NDS value of 1.5 was adopted. The cross-section dimensions were aligned with the results from the frame cross-sectional optimization for Douglas Fir conducted in the previous section. The minimum required load capacity was derived from the load calculations presented earlier (Appendix). The iteration steps range from 12.5 millimeters to 25 millimeters, with each step

incrementing by approximately 5 millimeters. Traditionally, the tenon thickness to mortise thickness ratio is 1/3 to prevent weakening of the mortised stock. This study, however, examines this ratio using the equivalent steel bolt method to determine the optimal ratio for maximum capacity. Ten diameter values and ten thickness ratios ranging from 1/8 to 12/8 were used for the thickness ratio optimization iteration process.



Capacity vs Diameter for different tm/ts Ratios

Figure 3.12: The tenon to mortise thickness Ratio compared to capacity

Based on the graph represented in figure 3.12, a tm/ts ratio of approximately 0.5 appears to be optimal for maximizing capacity across different diameter ranges. At this ratio, the capacity curves for different diameters tend to be closer together and higher overall compared to lower ratios. While higher ratios might show slightly better capacity for some specific diameter ranges, a ratio of 0.5 seems to provide a good balance of strength and efficiency across a wider range of peg sizes. While the results align with traditional rules of thumb regarding the tenon-to-mortise thickness ratio, it's crucial to remember that tension might not be the primary concern in tenon design.

Bending and shear failures can govern tenon performance. Therefore, further analysis considering these failure modes is necessary to determine the optimal tm/ts ratio for overall joint strength and stability. Therefore, further investigation is necessary to examine how the tenon-to-mortise thickness ratio influences joint capacity when subjected to shear loading.

The abrupt shift in the graph's trajectory is attributed to a change in the predominant failure modes. Initially, for all ratios, mode vd exhibits the lowest value, thereby governing the failure. Consequently, the trend line for all ratios remains consistent at the outset, as tm/ts is not factored into mode vd. Subsequently, the trend undergoes a change with a uniform slope, as one of the modes Im, Is, or Id consistently governs, maintaining a constant ratio while other variables remain unchanged.

Figure 3.13 and table 3.3 presents the optimal peg diameter that yields the highest capacity while maintaining acceptable spacing, based on the input variables. The green row in table 3.3 highlights the most optimal result, with the full results available in Appendix. The table showcases 4 selected thresholds from a total of 30 steps in the iteration.

Diameter(mm)	L.e(mm)	L.s(mm)	L.v(mm)	L.g(mm)	Joint capacity(kN)	Joint Status
16.51	22.21	27.76	16.66	16.66	4.48	Not Acceptable
16.764	22.9	28.62	17.17	17.17	4.62	Acceptable
26.416	56.85	71.07	42.64	42.64	11.47	Acceptable
26.67	57.95	72.44	43.46	43.46	11.69	Not Acceptable

Table 3.3: The Optimal Dimensions and their Corresponding Utilization Factors and Weight

The results highlight the significant impact of optimizing joint geometry configuration, particularly in relation to peg diameter. It appears that even a moderate adjustment of 60% in peg diameter can lead to a substantial 150% increase in joint capacity. This underscores the

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importance of careful consideration of geometric parameters when designing timber connections to achieve optimal structural performance.

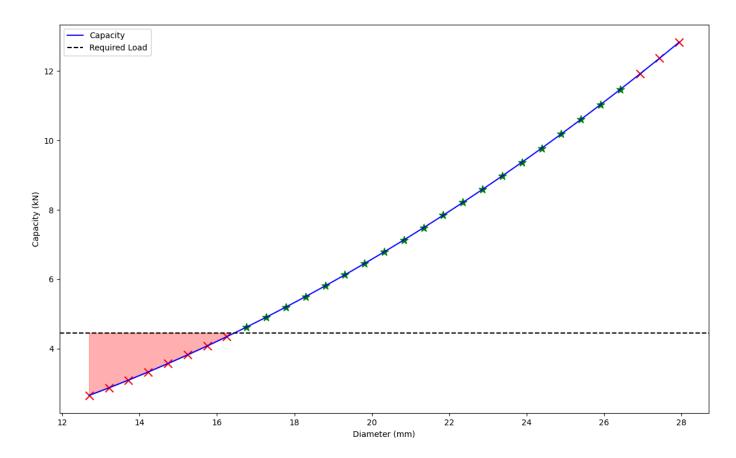


Figure 3.13: optimisation results for PMT joint based on Steel Equivalent Method, green stars and red crosses indicate acceptable and unacceptable spacing around the peg or required load bearing capacity

Geometry Optimisation of PMT Joints Using Numerical Model

While the equivalent steel bolt method provides a conservative estimate for ductile failure spacing requirements, an FEM model was developed to refine these analytical predictions. Furthermore, given the FEM software's capacity to handle intricate geometries, the model was employed in an optimization loop to assess the impact of complex shapes on PMT joint capacity.

FEM setup

To establish and validate the initial FEM, a study by (Miller 2004) was utilized. This research details both numerical and experimental approaches for conducting strength-based analyses on pegged PMT joints. Following Miller's methodology, a three-dimensional FEM was constructed with the objective of accurately predicting the 5% offset yield load of mortise and tenon joints subjected to tension. The 5% offset yield load, as defined by (ASTM D5764-23), Standard Test Methods for Evaluating Dowel-Bearing Strength of Wood and Wood-Based Products, involves identifying the initial linear portion of the load-deflection curve. Subsequently, a line parallel to this initial segment is offset by 5% of the peg diameter along the deflection axis. The intersection of this offset line with the load-deflection curve establishes the yield load. Upon successful validation, the FEM model was further utilized to predict yield loads for PMT joints exhibiting diverse geometrical properties, extending beyond the scope of the physical tests reported by (Miller 2004) . The finite element modeling was conducted by ANSYS 2023 R2, a commercially available software program. The analyses were performed on an ASUS ROG G513 laptop with an AMD Ryzen 7 processor, running the Microsoft Windows 10 operating system.

Model's detail

To accurately model the physical model done by (Miller 2004), a FEM that replicates tenison testing (figure 3.14.a) was developed. To accurately replicate the physical testing conducted by Miller (2004), a FEM (figure 3.14.b) simulating the tension test configuration was developed. The dimensions of the PMT joint are presented in Table 3.4. The peg, mortise, and tenon were partitioned into three subvolumes which let us define a different mechanical properties and geometry for each. Each subvolume was assigned a flexible stiffness behavior.

Geometry of FEM	Dimensions
Distance of tenon's end to center of the peg (Lv)	7.62 cm
Depth of tenon from the center of peg (le)	7.62 cm
Tenon thickness	4.826 cm
Gap between the mortise and tenon	0.127 cm
Peg diameter	5.08 cm

Table 3.4:	the geometrical	details o	of the FEM
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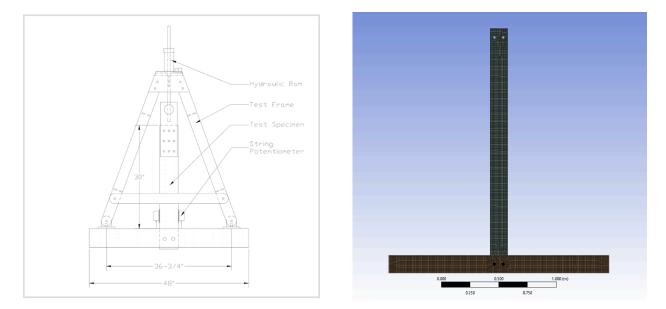


Figure 3.14: a) Tension Testing Apparatus from Schmidt and MacKay (1997), b) Developed FEM model

Material Model

Although (Miller 2004) mentioned the material properties and values in their report, new values for some of these values have been performed and some values updated based on more recent sources to achieve a higher accuracy. Formula by (Yang 2005) is used to calculate shear moduli:

$$G = \frac{E}{2(1+V)}$$

The orthotropic material properties of Douglas Fir were simulated by assigning **orthotropic elasticity** in the elastic region, and Orthotropic stress and strain limits.

Although simulating the plastic behavior of the timber was not the primary interest of this, a **bilinear stress-strain relation** was used to facilitate the determination of the yield load. Plasticity of the material was modeled by assigning **bilinear isotropic hardening**. The **Hill yield criterion** was assigned to determine when yielding occurs based on the applied stresses and the material's anisotropic yield strengths. Given that Douglas fir is an orthotropic material, the FEA model employed the "Hill Yield Criterion" to account for the material's plasticity. The Hill criterion is particularly suitable for orthotropic materials, as it provides a framework for

predicting yield behavior under multiaxial loading conditions. Based on (Miller 2004)'s report on physical tests on Douglas Fir, the tangent stiffness perpendicular to the grain was half of MOE. Moreover, when the material was loaded perpendicular to the grain direction, the tangent stiffness approached plastic behavior and could be assumed to be close to 0.1E. Due to the minimal difference in values between the radial and tangential directions, the same elastic modulus E (mean value) was applied to both for simplicity. Similarly, a single Poisson's ratio µ was utilized for both the radial-longitudinal and tangential-longitudinal planes.

Parameter	Value	Unit
E _x	16500	MPa
E _{v =} E _z	960	MPa
$G_{xy} = G_{xz}$	810	MPa
G _{yz}	350	MPa
V _{xv (LR or LT)}	0.37	
V _{yz (RT or TR)}	0.38	
V _{xz (TLor RL)}	0.032	
δ _{u,c}	0.0001	MPa
f _{t.0}	57	MPa
f _{t.0} f _{c.0} f _{t,90}	36.9	MPa
f _{t,90}	1.8	MPa
f _{c,90}	7.2	MPa
f _v	6.9	MPa
f _{roll}	9.7	MPa

Table 3.5: the material properties of the FEM

Contact

Four bonded contact regions (Figure 3.15) were defined: two for each peg in contact with the mortise, and one for the tenon. No contact interaction was defined between the face of the tenon and the mortise, as the loading was assumed to be purely tensile, with the pegs primarily responsible for stress transfer.

Meshing

The Hex Dominant meshing method, incorporating quad and tri elements, was employed for all subvolumes. Specific contact typing and face sizing was applied to both contact and target surfaces within each interaction to facilitate the generation of a finer mesh at the contact interfaces.

A **mesh refinement study** (Table 3.6) was conducted to ensure the accuracy of the finite element analysis. Three levels of mesh refinement were evaluated, with the results demonstrating a convergence in the predicted structural response. The maximum difference in calculated values between the finest and coarsest meshes was less than 3%. Consequently, the intermediate mesh density was selected for subsequent analyses, providing a balance between computational efficiency and solution accuracy.

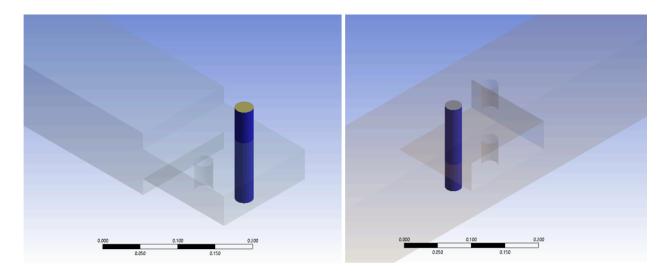


Figure 3.15: Four bonded contact regions a)the contact region between tenon and pegs, b) the contact region between mortise and pegs

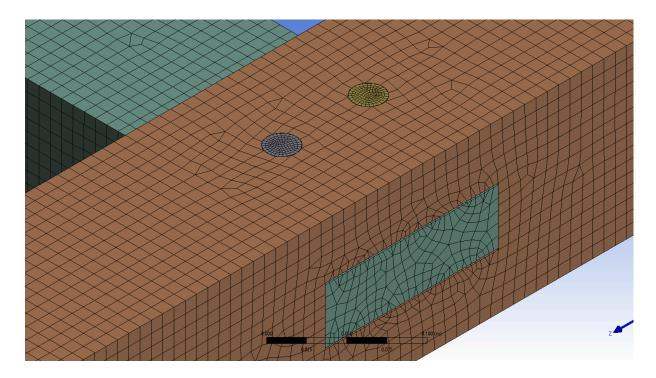


Figure 3.16: Meshing quality and properties of the FEM

Force (N)	Deflection (mm)	Force (N)	Deflection (mm)	Force (N)	Deflection (mm)
0	0	0	0	0	0
8207,5	1	8340,5	1	8504,8	1
15507	2	15856	2	16288	2
21820	3	22321	3	23048	3
27866	4	28482	4	29469	4
33722	5	34476	5	35717	5
39434	6	40356	6	41845	6
45053	7	46142	7	47868	7
50600	8	51838	8	53787	8
56085	9	57453	9	59603	9
61508	10	62977	10	65326	10
	N = 32821		N = 150826		N = 521064
	E = 8698		E = 41016		E = 131451

Table 3.6: the mesh refinement results

Boundary and Loading Condition

A bearing load was applied to the end face of the tenon, acting in the longitudinal direction (parallel to the grain) of the tenon. Given that the focus of the analysis was on the macroscopic load-deflection response, convergence was assessed by examining the applied load and the corresponding deflection at a node located away from the peg region. Two fixed supports were applied to the cross-section of the mortise model to more accurately replicate the boundary conditions employed in the physical tests conducted by .

Validating FEA setup

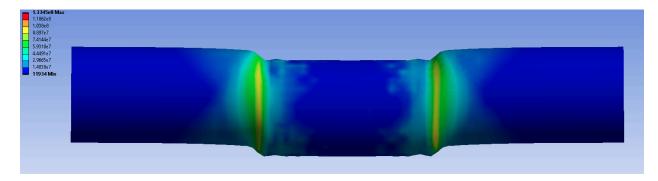


Figure 3.17: Plastic deformation of the peg model

Validation ensures the FEA model accurately reflects real-world behavior. While any model is an approximation, validation confirms it meets its purpose. Using commercial software like Ansys, we assume the underlying numerical methods are sound, focusing on whether our model setup captures the real-life model adequately. An iterative process of reviewing results and adjusting the model setup was undertaken to ensure reasonable deformation behavior. Upon observing the formation of four hinges in the peg (Figure 3.18), further refinement was performed to enhance the accuracy of the results.

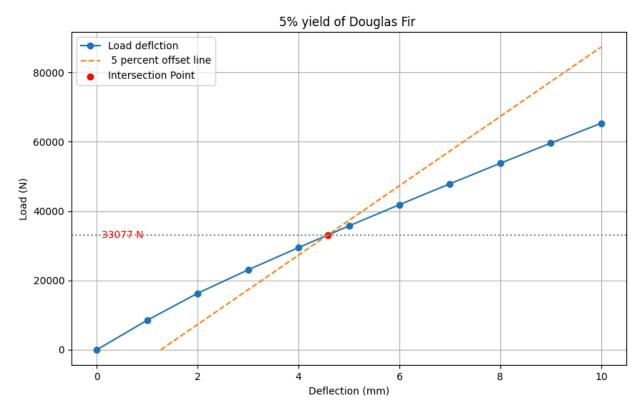


Figure 3.18: the validation result for 5% offset yield mode

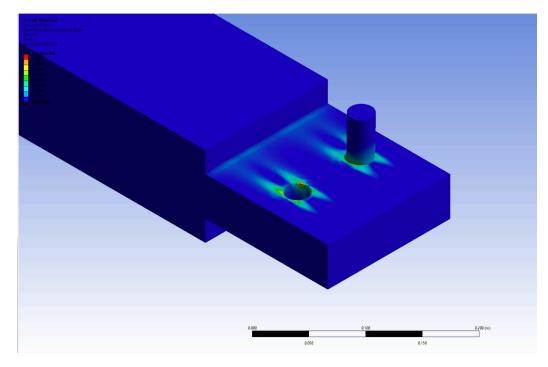


Figure 3.19: the plastic deformation of the peg model in the tenon

The 5% yield method was applied to the load-deflection graph generated by the finite element model. Results (table 3.7 ,and figure 3.18) indicated that the model was capable of predicting the mean value results obtained from the 5% yield method of physical testing, with an accuracy of 25%. The model developed in this study exhibited slightly higher accuracy compared to the one developed by (Miller 2004), and additionally, demonstrated increased plasticity. This enhanced performance can be attributed to the more detailed plasticity model explained earlier in the thesis. This higher plasticity can be beneficial in the optimization process. As the 5% yield increases, it may fail to intersect with the line, and higher plasticity aids in modeling the yield value more accurately.

Table 3.7: the Comparison of the result for 5% offset yield mode of physical, and the FEM and numerical model developed by Miller

Physical Yield load (N)	Modeled Yield load(N)	Ratio	Modeled Yield load by Miller (N)
26,244	33,077	1.25	33539

Optimization Loop

To examine how the placement of pegs affects joint performance, 25 different scenarios were created, with each scenario representing a unique arrangement of pegs within the mortise-tenon joint. These arrangements were methodically designed to cover a wide range of positions, enabling a thorough analysis of how changes in geometry impact load deflection and stress distribution. The specifics of these scenarios are detailed in Table 3.8. Each scenario was analyzed using FEM, allowing for the assessment of mechanical responses under simulated loading conditions. This systematic approach ensures that the study captures the subtle details of joint performance across various geometries, ultimately leading to the identification of the best arrangements for improved structural strength. The location of the pegs within the joint is determined by two factors: 'y', representing the peg's distance from the tenon's side edge, and 'h', representing its distance from the tenon's bottom edge (figure 3.20). In this analysis, we assume a consistent peg diameter of 1 inch and symmetrical placement of the left and right pegs.

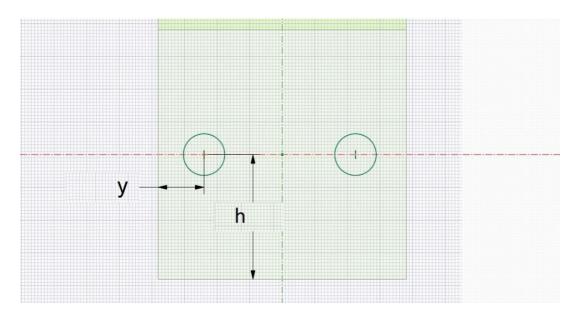


Figure 3.20: the plastic deformation of the peg model

Case Number	y (mm)	h (mm)	Case Number	y (mm)	h (mm)
1	25	76.2	14	35	101.6
2	30	76.2	15	35	127
3	35	76.2	16	35	50.8
4	40	76.2	17	35	25.4
5	45	76.2	18	40	101.6
6	25	101.6	19	40	127
7	25	127	20	40	50.8
8	25	50.8	21	40	25.4
9	25	25.4	22	45	101.6
10	30	101.6	23	45	127
11	30	127	24	45	50.8
12	30	50.8	25	45	25.4
13	30	25.4			

Table 3.8: Details of variations in the optimisation loop

After the model was validated, it was used as the basis for optimizing the joint geometries. The validated FEA model was used to create data for all 25 cases, which allowed for a thorough analysis of how different peg placements affect how the joint performs. The outputs included load deflection, stress distribution, and failure modes, which were systematically recorded and analyzed.

Methodology - Data Collection

Gathering data was a key part of this study, as it gave us important information about how well the mortise-tenon joints performed with different peg placements. We collected a full set of results for each of the 25 different peg configurations. These results focused on key measurements like the amount of force applied, the highest stress levels in the pegs, tenon, and mortise. This information was essential for understanding how the placement of the pegs affected the overall strength and stability of the joints.

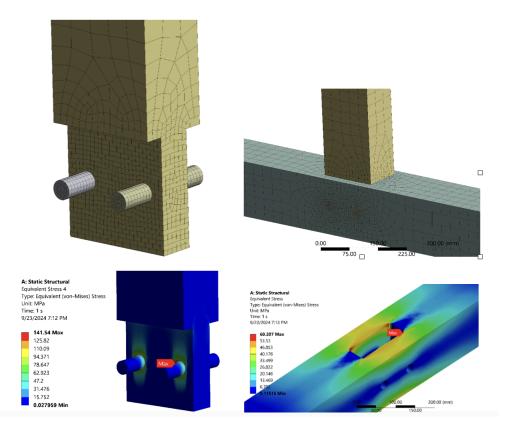


Figure 3.21: Results of the FEA of one the optimization cases (Case 2)

The FEA simulations were carried out in 21 incremental steps, allowing close examination of how the joint responded as it was gradually deflected by 10 mm. This step-by-step increase in deflection helped us understand how the joint behaved under growing loads, and it captured the important shift from elastic (reversible) to plastic (permanent) deformation. By carefully controlling the deflection in smaller increments, we ensured that the stress distribution and force responses were precisely recorded at different loading stages. All the data gathered was systematically organized and stored in an Excel spreadsheet, which acted as a central database for further analysis. This organized approach made it easy to access and efficiently work with the data, including visualizing it in helpful ways. The Excel file had separate columns for each of the 25 different joint configurations, detailing the corresponding force values and stress measurements for the pegs, tenon, and mortise.

This dataset is crucial for upcoming optimization analyses, as it enables us to pinpoint the best peg placements for improved joint performance. By examining the connection between peg location and stress distribution, the study aims to offer practical insights to enhance mortise-tenon joint design. The data analysis was performed using MATLAB (appendix), a powerful computational tool that simplified the processing and visualization of the finite element analysis (FEA) results. The main goal of the analysis was to calculate the yield load for each of the 25 peg configurations using the established 5% offset method, a common technique for determining yield points in load-deflection curves. To begin the analysis, a MATLAB script was developed to load the data collected from the FEA simulations. The data was efficiently organized by the script, and key metrics such as applied force and corresponding deflection values were extracted for each case. Once the data was loaded, the analysis focused on calculating the yield load, which is critical for understanding the performance limits of the mortise-tenon joints. To determine the yield load for each case, a line was drawn parallel to the initial linear portion of the load-deflection curve, starting at an offset of 0.5 mm. The intersection of this offset line with the curve indicated the yield load. Yield loads were calculated for all 25 cases. MATLAB code was used to generate plots visualizing the results, including load-deflection curves for each configuration with highlighted yield points. These plots allowed for easy comparison between different peg placements and their impact on stress distribution within the joint. The visualizations helped identify trends and patterns in the data, contributing to the understanding of how peg positioning affects joint performance and informing design

optimization for mortise-tenon joints. Overall, the MATLAB data analysis was instrumental in converting raw simulation data into useful insights, supporting the study's goal of improving joint performance through informed design choices.



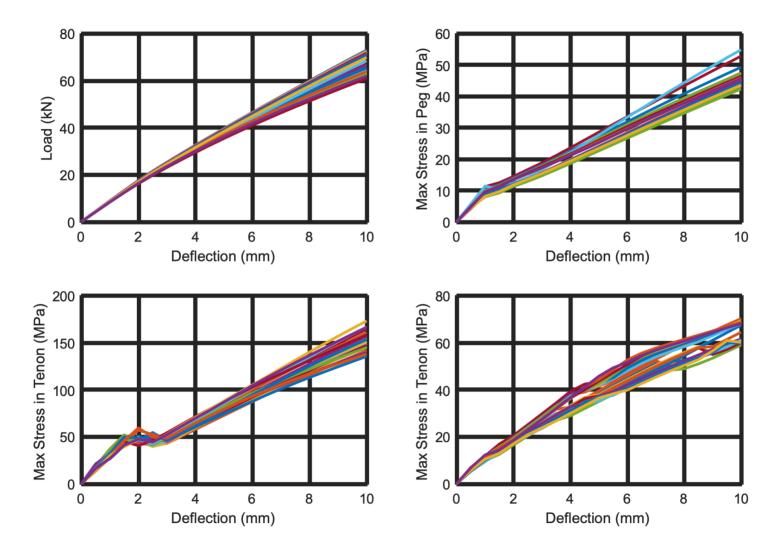


Figure 3.22: load and corresponding maximum stress in each elements vs deflection

This study visualized the results of Finite Element Method (FEM) simulations on 25 different mortise-tenon joint designs. Graphs were used to demonstrate how forces and stresses varied across these designs, providing a comprehensive view of the joints' behavior. One key finding

was that the placement of the peg significantly influenced the mechanical response of the joint. Load-deflection curves showed how different peg positions affected the joint's strength and stiffness. Some configurations were clearly stronger and more rigid than others. Furthermore, visualizations of the maximum stress on different joint components (peg, tenon, and mortise) revealed how design choices impacted stress distribution. This allowed for the identification of configurations that minimized stress concentrations, which is crucial for improving the joint's durability and longevity. In essence, these visual representations effectively captured the complex relationship between the joint's geometry and its performance under load. By highlighting the impact of peg placement on both force distribution and stress concentrations, this study provides valuable insights for optimizing the design of mortise-tenon joints.

The analysis does not solely focus on maximizing the yield load. A crucial aspect of the study is the consideration of stress levels in the mortise and tenon. The design constraint stipulates that the pegs must fail before the mortise or tenon, which serves to protect the integrity of the primary structural components. Therefore, the optimal peg configuration must strike a balance between achieving a high yield load and keeping stress levels within safe limits.

Analysis of the data revealed clear trends in how different peg placements affected both the strength and stress distribution within the mortise-tenon joint. Each of the 25 configurations was assessed based on its yield load (the maximum force it could withstand before permanent deformation, calculated using the 5% offset method) and the highest stress levels observed in the peg, mortise, and tenon components during loading.

Yield Load Variation: As shown in Figure 3.22, there was significant variation in yield load across the different configurations. Some peg positions clearly resulted in a stronger joint, indicating that specific geometries are better at distributing forces. For example, placing the peg near the edges of the mortise (cases 7, 9, 11, 13, 15) generally led to lower yield loads. This is likely due to less efficient load transfer and higher bending stresses caused by stress concentration in those areas.

In contrast, the strongest configurations were those with pegs positioned towards the center of the allowable area. This is likely because having more material around the peg allows for better

stress distribution, reducing stress concentrations and increasing the load the joint can withstand before yielding.

Stress Distribution

In addition to analyzing yield load, this study carefully examined the maximum stress levels within the mortise and tenon components (figure 3.24). This analysis revealed that certain peg configurations, particularly those where the peg was positioned close to the edges of the mortise (Cases 7 and 9), led to higher stress concentrations in either the mortise or the tenon. Similarly, almost all configurations with an "h" value of 50.8 mm (Cases 16, 20, and 24) showed elevated stress levels in the tenon. These findings emphasize the importance of considering both yield load and stress distribution when optimizing joint design. While a high yield load is desirable, it's equally important to ensure that stress concentrations remain within safe limits to prevent the joint from failing prematurely.

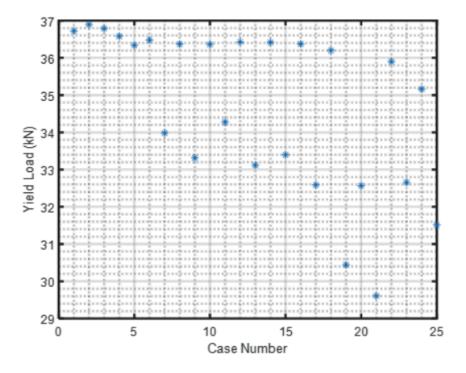


Figure 3.23: case numbers and their corresponding yield load

The ultimate goal of this study was to pinpoint the optimal peg configuration that maximizes yield load while keeping stress levels within acceptable limits. A systematic evaluation of all 25 configurations revealed several promising candidates that exhibited a good balance between high yield strength and low stress concentrations in the mortise and tenon. Cases 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, and 18 demonstrated the highest yield loads, with less than a 3% difference between them. However, when considering maximum stress values in the tenon, Cases 2, 11, 15, and 23 showed the lowest values.

Taking both factors into account, configuration number 2 emerged as the best overall performer. It exhibited a high yield load combined with minimal stress on the tenon, making it the optimal choice among the 25 configurations tested.

Effect of Peg Stress Values

This study found a strong link between how much force a mortise-tenon joint can handle before permanently deforming (yield load) and the highest stress levels in the pegs. Joints with higher yield loads generally had lower peak stress in the pegs. This is because of how stress concentrates and spreads within the joint. Stress concentration happens when external forces cause stress to build up in specific areas of a material. In mortise-tenon joints, the pegs, which transfer load between the tenon and mortise, can create high-stress zones around where they're inserted. This is due to the peg's shape disrupting the material's continuity, causing stress to increase locally. When pegs have high stress concentrations, the whole joint is weaker. High peg stress can cause early failure, as the material might yield or break at these stress points before the entire joint reaches its maximum load capacity. Therefore, designing peg configurations that minimize stress concentration is vital for improving the joint's overall strength and performance.

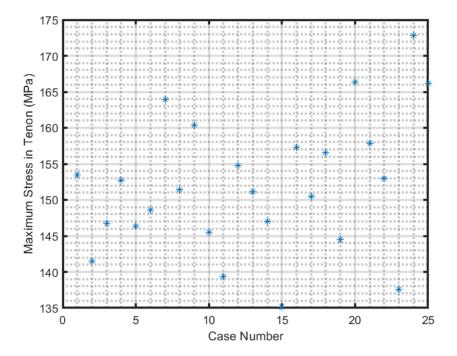


Figure 3.24: case numbers and their corresponding maximum stress in the tenon

Conversely, effective stress distribution plays a vital role in maximizing the yield load of mortise-tenon joints. Stress distribution refers to how applied forces are spread across the joint and its components. A well-distributed stress profile allows the joint to withstand higher loads without reaching critical stress levels that could lead to failure. In configurations where stress is evenly distributed, the load is shared more effectively among the pegs, mortise, and tenon. This distribution reduces the likelihood of localized stress peaks, allowing the joint to endure greater external forces. As a result, the yield load increases, enhancing the joint's total capacity to withstand loads.

The analysis underscored the inherent trade-offs in joint design. While it is desirable to maximize yield load, achieving this goal often involves compromises in other performance metrics. For example, configurations that positioned pegs too far from the mortise edges (15, 23) might yield lower stress concentrations but also resulted in reduced yield loads.

Understanding these trade-offs is essential for making informed design decisions. The study emphasizes the need for a holistic approach to joint design, where multiple factors are considered simultaneously. Designers must weigh the benefits of higher yield loads against the potential risks associated with elevated stress levels in the mortise and tenon.

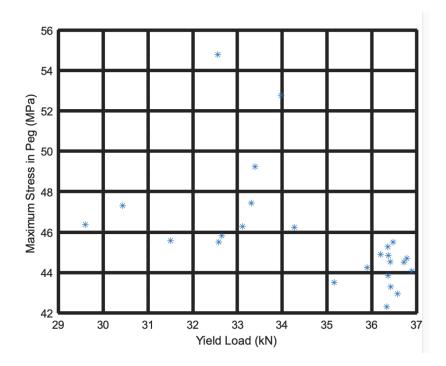


Figure 3.25: Yield load - maximum stress in the pegs

Developing Connection Design Methods Based on Rule of Thumb and Carpenters Recommendation

After optimizing the pegged mortise and tenon joint and finalizing its geometry, three additional joint categories were designed: Scarf, Blind Mortise Tenon, and Gooseneck joints. These designs were based on established carpentry practices and the recommendations of experienced carpenters, drawing upon generations of knowledge in timber framing.

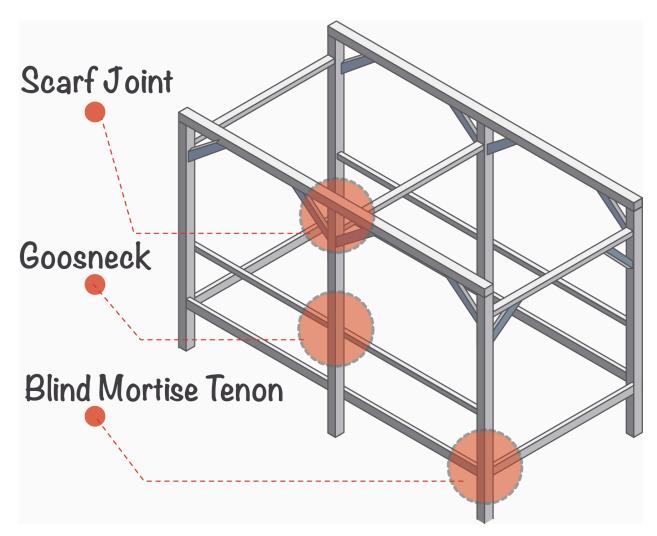


Figure 3.26: The Position and type of Joints in the timber structure

Scarf joint

Scarf joints, also known as splice joints (Figure X), are used to connect two members end-to-end (Hewett 1980). This technique is particularly useful when the required length of a member exceeds the available material. Considered the strongest method for lengthening timber without

glue (Thelandersson 2003), the scarf joint employs a pair of matching angled cuts that are secured together with pegs (Branco 2015).

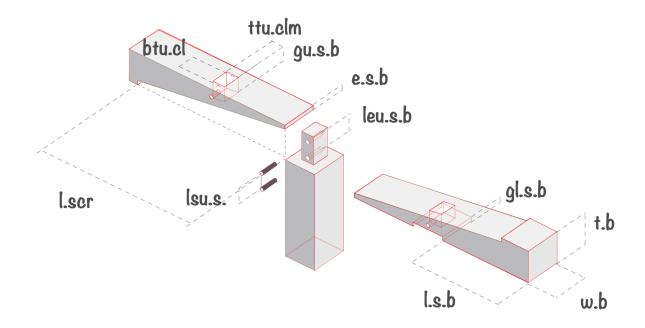


Figure 3.27: the Scarf joint details used in the case study

Based on (Fountain 2009), to achieve structurally sound and aesthetically pleasing scarf joints in timber framing, the following design recommendations are proposed (figure 28):

- Length: The scarf joint's overall length should be three times the height (or depth) of the timber members being joined. This ensures sufficient surface area for load transfer and a visually balanced joint.
- Abutment Height: The height of the abutments at each end of the scarf should be one-sixth of the timber's height. This dimension can be rounded to the nearest 1/16th or 1/8th of an inch to simplify layout.
- **Centerline Positioning:** When a scarf joint is located near a knee brace, its centerline should be offset 5 1/2 inches from the brace's bearing point on the adjacent post. This strategic offset prevents interference between the brace's tenon and the upper section of the scarf, facilitating a clean and efficient construction process.

These recommendations, derived from established carpentry practices and a focus on proportionality, provide a framework for designing robust and visually harmonious scarf joints in timber frame structures.

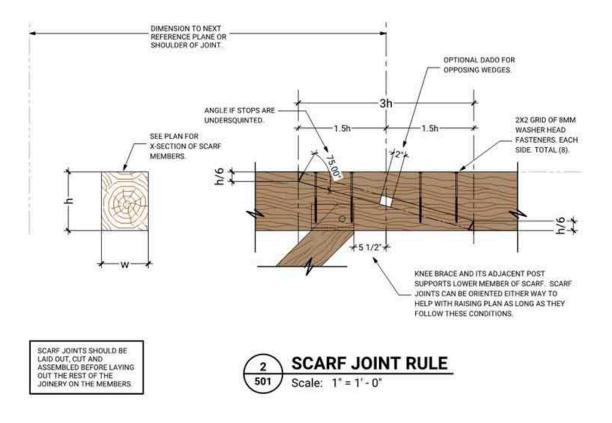


Figure 3.28: the Scarf joint rule of thumbs detailing

Gooseneck Joint

Due to the lack of established design guidelines for gooseneck joints (Figure 3.29), a Finite Element Method (FEM) analysis was conducted to determine the optimal geometric configuration for this specific joint type. The same meshing details and material properties used in the analysis of the Pegged Mortise and Tenon (PMT) joint were applied to ensure consistency and comparability. For this analysis, the gooseneck joint was subjected to a pure tension force to evaluate its performance under tensile loading. This FEM-based approach allowed for a detailed investigation of the joint's behavior and the identification of the most efficient geometric ratios for maximizing its strength and stability.

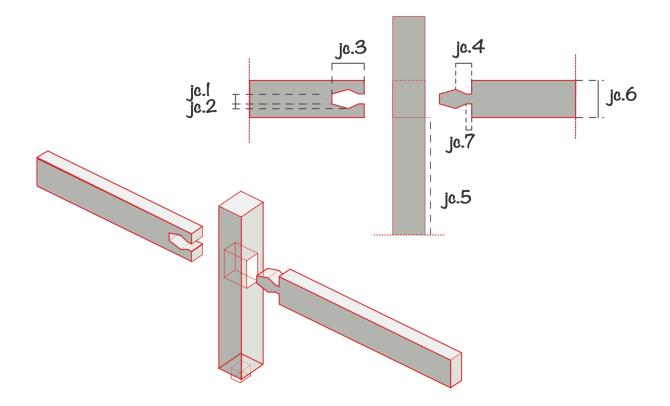


Figure 3.29: the Scarf joint drawing with variables used in optimisation

The variables of the optimization loop are shown in the table 3.9. Figure 3.30 presents the results of finite element analysis (FEA) conducted on 25 distinct joint geometries. The analysis involved applying a 5 mm displacement to the end of each joint and measuring the resulting tensile force and stress distribution. The results clearly demonstrate that variations in joint geometry significantly influence both the magnitude of tensile force and the stress concentration. This finding underscores the importance of the optimization process in identifying a geometry that minimizes stress while maximizing tensile force. The optimal geometry, as determined through this process, exhibits distinct characteristics that differentiate it from the other configurations. Figure 3.31 illustrates the yield strength of the structure for each of the analyzed cases.

jc.4 (in)	jc.1 (in)	jc.2 (in)	jc.4 (in)		
Case 1	2.5	1.8	0.8		
Case 2	2.5	2.1	0.9125		
Case 3	2.5	2.4	1.025		
Case 4	2.5	2.7	1.1375		
Case 5	2.5	3	1.25		
Case 6	3.875	1.8	0.9125		
Case 7	3.875	2.1	1.025		
Case 8	3.875	2.4	1.1375		
Case 9	3.875	2.7	1.25		
Case 10	3.875	3	0.8		
Case 11	5.25	1.8	1.025		
Case 12	5.25	2.1	1.1375		
Case 13	5.25	2.4	1.25		
Case 14	5.25	2.7	0.8		
Case 15	5.25	3	0.9125		
Case 16	6.625	1.8	1.1375		
Case 17	6.625	2.1	1.25		
Case 18	6.625	2.4	0.8		
Case 19	6.625	2.7	0.9125		
Case 20	6.625	3	1.025		
Case 21	8	1.8	1.25		
Case 22	8	2.1	0.8		
Case 23	8	2.4	0.9125		
Case 24	8	2.7	1.025		
Case 25	8	3	1.1375		

Table 3.9: the variables of the optimisation loop of the Scarf joint

Notably, cases 6 through 25 exhibit nearly identical yield strength values. This observation suggests that, with the exception of cases 1 to 6, where the geometric parameter jc4 is minimized, the yield strength remains relatively consistent across the range of

geometries. This finding highlights the influence of jc4 on the structural performance. Figure 3.32 presents the maximum principal stress observed in both the male and female components of the joint.

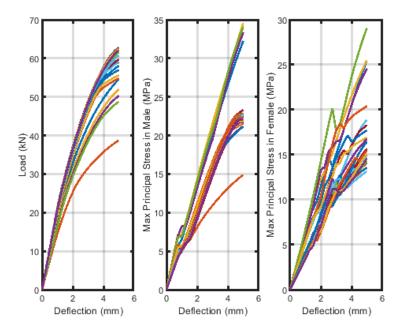


Figure 3.30: the variation of stress and yield loads - deflection with different case numbers

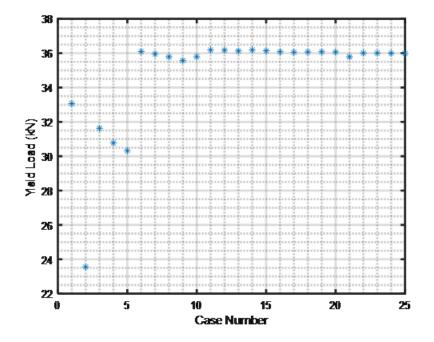


Figure 3.31: case numbers and their corresponding yield load

Among the cases exhibiting the highest yield strength, cases 13 and 15 demonstrate the lowest principal stress in both the male and female components, as illustrated in Figure [Figure number].

Figure [Figure number] presents the maximum von Mises stress for each case. Notably, case 15 exhibits the lowest total von Mises stress across both the male and female components.

Based on the analysis of both principal stress and von Mises stress, alongside yield strength, case 15 emerges as the optimal geometry due to its superior performance across these critical metrics. This case effectively minimizes stress concentrations while maintaining high yield strength, making it the most suitable choice for the intended application.

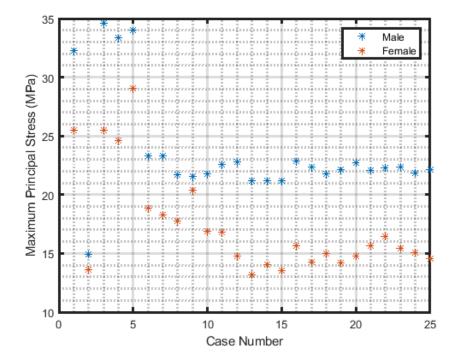


Figure 3.32: case numbers and their corresponding maximum principal stress

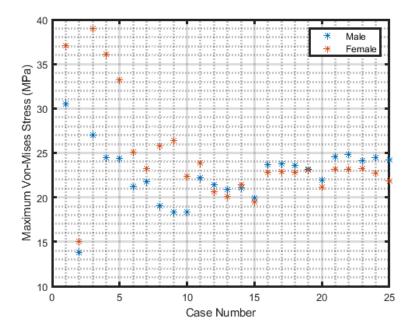


Figure 3.33: the Scarf joint drawing with variables used in optimisation

Final Design

Having determined the footprint, cross-sectional properties, and joint details, the final structural design is illustrated in Figure 3.34.

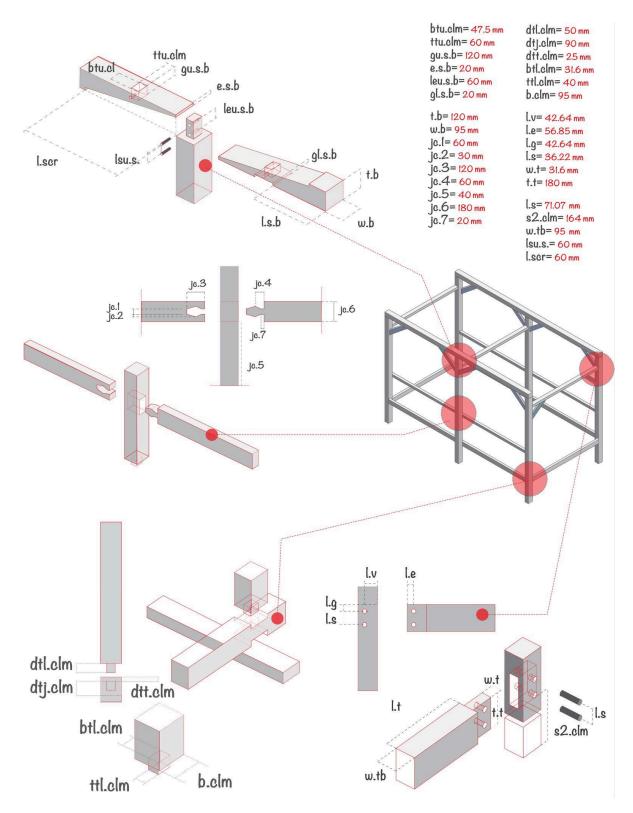


Figure 3.34: the final structural design

Conclusion and Discussion of Case-Study

- The preliminary design and layout chosen for this specific timber frame inherently restricts the potential for automation to the parameters defined within this particular system. This observation underscores a crucial consideration in the development of 'Lock n Load': the initial layout of any structural system fundamentally constrains the scope of design automation to the variables explicitly established within that system. Consequently, the first and pivotal step in automating any design process is the deliberate selection of both the structural system itself and its specific variation.
- In this case study, a simplified approach was initially taken, assuming rigid connections between primary beams and columns, and simply supported connections for eaves beams and joists. However, for the finite element method (FEM) analysis, a more realistic representation was adopted, considering the connections as semi-rigid. This highlights a crucial insight for the development of 'Lock n Load': the ability to define connections with varying stiffness based on their analyzed behavior is essential. This flexibility will allow for more accurate modeling and simulation of real-world structures, leading to improved design and performance predictions.
- Prior to initiating any structural computations, it is imperative to define the material properties of the timber used in the design. Therefore, in developing 'Lock n Load,' incorporating a material library would be advantageous for designers, enabling them to readily access and utilize pre-defined material properties. It's also critical to ensure that within the 'Lock n Load' workflow, the input of material properties be provided before any structural calculations.
- A load calculator can significantly simplify the design process for designers, particularly by automating the input of environmental factors. Since load calculations also rely on geometry variables, it's essential that within the development of 'Lock n Load,' the load calculation method is executed only after the user has finalized the geometry and material output. This ensures accurate and relevant load calculations based on the specific design parameters provided by the user.
- Safety and modification factors should be generated through an interaction between the built-in computation component and the selected material type. **This approach ensures**

that both the specific element material type and its designated service class are taken into account when determining appropriate safety and modification factors.

- Cross-sectional optimization of timber elements was found to be effective in achieving significantly lower utilization factors while maintaining approximately the same overall weight.
- In analytical analyses of timber joints, unlike other elements in timber structures, the applicable methods can be restricted to specific types of timber. Therefore, in the development of Lock and Load, it is crucial to clearly specify which types of timber each specific method is suitable for.
- In the analytical case study, the focus was solely on the tensile capacity of the joint. However, it is recognized that joints can be subjected to other types of loading, such as shear and bending, which also warrant analysis. Therefore, it's important that Lock and Load be equipped to handle and provide for different types of loading that a building might experience.
- In the analytical optimization of the PMT joint, a tm/ts ratio of approximately 0.5 was found to be optimal for maximizing capacity. This aligns with the findings of (Hu 2021), who recommended a width-to-length ratio (w < I < 2w) for optimal joint performance. However still the effect of shear and bending should be examined.
- Optimizing the geometry of PMT joints resulted in an approximate 10% reduction in stress on the base materials and a 17% increase in yield load. Although the initial simulation stages were validated using physical experiments, further validation is required to confirm the accuracy of the FEM optimization loop results.
- This study utilized FEM analysis to determine an optimal geometric ratio of jc.4 : jc.1 : jc.2 = 5.25 : 3 : 0.9125 for gooseneck joints in timber structures under tensile loading. This finding offers valuable guidance for designing such joints, but further research is needed to assess the impact of different timber species, joint sizes, and loading conditions, including bending moment and stiffness optimization, on this optimal ratio.
- Given the discrepancy between FEM and analytical model results, "Lock n Load" should empower designers with the flexibility to customize variable values within the platform.

• To automate Eurocode-based structural design, the system must generate the following load outputs: ULS (instantaneous, medium-term, permanent), SLS, and four creep and deflection factors.

"Technology is best when it brings people together."

Matt Mullenweg

Lock n Load

This section introduces Lock n Load and its purpose. Lock n Load is a digital web-based tool designed to simplify, improve, and integrate the process of delivering, designing, optimizing, and assembling timber shelters for emergency use after disasters. This tool aims to benefit shelter-seekers, shelter designers, and other key stakeholders involved in the supply chain.

Front-End Functionality

Lock and Load is composed of four key components: the **Designer Panel**, the **Shelter-seekers panel**, the **CNC interface**, and the **Timber providers network** (figure 4.1).

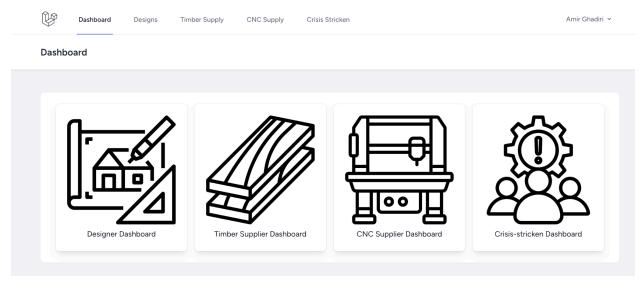


Figure 4.1: the homepage of Lock n Load

Designer Dashboard

When users access the designer dashboard, they can create a new timber frame design block. However, the case study's findings highlighted a key constraint: automating the design process across different structural systems necessitates a unique, **built-in** automation method for each system and its variations, at least within the scope of the methods explored in this thesis. Currently, the website administrators control how a structural system is designed, and only one type of timber frame is supported. However, users can still create their own custom designs within these limitations, as explained below.

When users begin the timber frame design process, they have the option to either select a pre-existing material from the library or create a new material block with custom properties (figure 4.3). These material properties (figure 4.4) will be used as inputs for subsequent calculations.

L9	Dashboard	Designs	Timber Supply	CNC Supply	Crisis Stricken		Amir Ghadiri 🗸
Desigr	s						
	Solid Log C	Construction	Frame Const	ruction	Timber Frame	Light Bearing Construction	Panel Construction

Figure 4.2: they have the option to utilize a built-in timber frame design module, lock n Load currently only supports one type of timber frame

It is crucial that the system obtains material property inputs during the initial design stages to enable accurate dead load calculations.

Das Das	shboard Designs	Timber Provider	CNC Provider	Shelter Seekers		Amir Ghadiri
ood Mana	agement				C	eate new mat
ld		r	name		type	
5			Fir	soft_wood		
4		Europe	ean Spruce	soft_wood		
3		Dou	ıglas Fir	soft_wood		
2		European Larch			soft_wood	
			test		hard_wood	

Figure 4.3: they have the option to utilize a built-in timber frame design module, lock n Load currently only supports one type of timber frame

eate new material			
eate new material			
Name	Туре		Bending strength
Douglas Fir	soft_wood	~	91
Tension strength parallel to grain	Tension strength perpendicular to grain		Compression strength parallel to grain
25	13		45
Compression strength perpendicular to grain	E-modulus 5%		E-modulus
24	12.1		11.2
Partial factor	Shear strength		Density
1.3	9		610
Modification factor permanent term	Modification factor medium term		Modification factor instantaneous term
0.5	0.6		0.9
Creep factor	Creep factor solid timber		End distance requirement
2	0.2		2
Vertical edge distance requirement	Peg spacing distance requirement		Edge distance requirement
1.5	2.5	÷	1.5

Figure 4.4: Material properties in one timber material block

Once the material properties have been selected, the user proceeds to input the predefined geometry variables for the structure, which include height, width, length, number of columns, and slab thickness (figure 4.5). This section empowers designers to further customize the timber shelter's dimensions according to their specific needs and preferences. Finalizing footprint inputs before load computation is essential, as the building's size and geometry directly influence the final load calculations.

After defining the material and geometry of the structure, the next crucial step is to determine the loads acting upon it. This tool offers users the flexibility to either manually input load values or utilize a built-in load calculator. Accurately calculating load combinations is essential in structural design. It ensures that structures can safely withstand various loads throughout their lifespan without unnecessary over-design. However, navigating the complexities of load

combination requirements in standards like Eurocode can be challenging even for experienced designers.

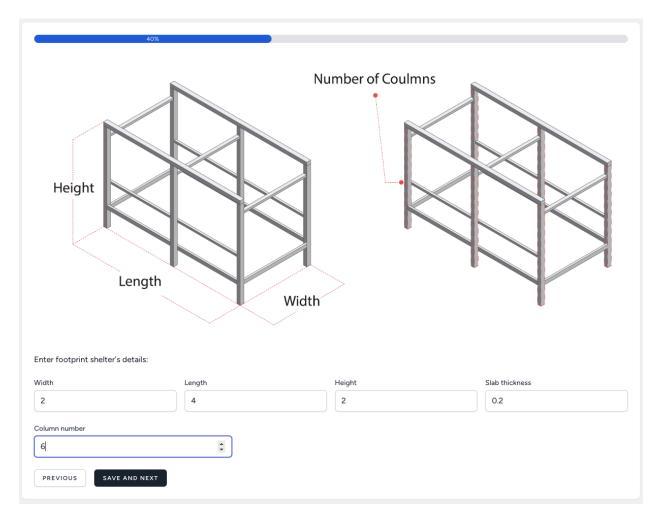


Figure 4.5: shelter footprint inputs

To address this, a Python-based load calculator script, detailed in Annex , has been integrated into the tool. This script simplifies the process of generating load combinations based on (EN 1990 6.10.) It assists designers in:

• **Optimizing and verifying new designs:** By accurately calculating the combined effects of various loads.

• Checking the suitability of existing designs: For specific locations and load conditions.

The load calculator generates load combinations for both **Ultimate Limit State** (ULS) and **Serviceability Limit State** (SLS) design scenarios. It considers **permanent**, **medium-term**, and **instantaneous** actions, providing the necessary factors for calculating combination values, **frequent values**, and **quasi-permanent** values of variable actions. This information is crucial for determining different types of deflection, including creep and net final deformation (illustrated in Figure 4.6).

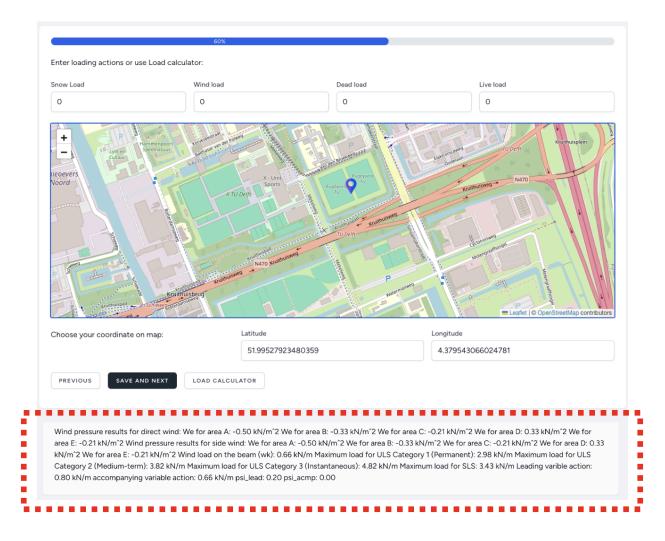


Figure 4.6: Load calculation outputs

By automating these calculations, the tool streamlines the design process, reduces the risk of errors, and ensures compliance with Eurocode requirements. This allows designers to focus on other critical aspects of structural design, confident that the load combinations are accurately and efficiently determined.

Once the loads on the structure have been determined, the next step involves defining the dimensions of its key supporting elements: primary beams, columns, bottom sills, and tie beams. Each of these elements is characterized by two key variables: width and thickness.

To facilitate this process, the tool offers users two distinct approaches:

- 1. **Direct Input:** Users with prior knowledge or specific dimensional requirements can directly input the desired width and thickness for each element. This allows for full control over the structural design (figure 4.7).
- 2. **Optimization:** Alternatively, users can leverage the built-in optimizer to determine the optimal dimensions for each element. This feature automatically calculates the most efficient width and thickness values based on the load calculations and predefined design constraints. This approach can help optimize material usage and structural performance (figure 4.8).

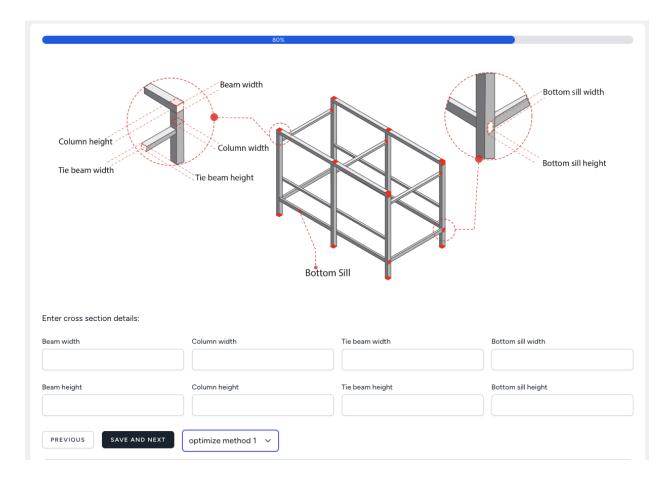


Figure 4.7: Manual inputs for cross-sectional design

bending_status : Acceptable, bending_utilisation : 26.27%, buckling_status_in_plane : Acceptable, buckling_status_out_of_plane : Acceptable, buckling_utilisation_in_plane : 2.98%, buckling_utilisation_out_of_plane : 11.13%, compression_status : Acceptable, compression_utilisation : 2.85%, final_utilisation : 86.75%, final_utilisation_status : Acceptable, length : 2.00 m, shear_status : Acceptable, shear_utilisation : 19.79%, sls_status : Acceptable, sls_utilisation : 86.75%, thickness : 149 mm, weight : 11.82 kg, width : 65 mm,

bending_status : Acceptable, bending_utilisation : 26.99%, buckling_status_in_plane : Acceptable, buckling_status_out_of_plane : Acceptable, buckling_utilisation_in_plane : 3.06%, buckling_utilisation_out_of_plane : 11.28%, compression_status : Acceptable, compression_utilisation : 2.88%, final_utilisation : 90.34%, final_utilisation_status : Acceptable, length : 2.00 m, shear_status : Acceptable, shear_utilisation : 20.06%, sls_status : Acceptable, sls_utilisation : 90.34%, thickness : 147 mm, weight : 11.66 kg, width : 65 mm,

bending_status : Acceptable, bending_utilisation : 27.74%, buckling_status_in_plane : Acceptable, buckling_status_out_of_plane : Acceptable, buckling_utilisation_in_plane : 3.14%, buckling_utilisation_out_of_plane : 11.44%, compression_status : Acceptable, compression_utilisation : 2.92%, final_utilisation : 94.13%, final_utilisation_status : Acceptable, length : 2.00 m, shear_status : Acceptable, shear_utilisation : 20.33%, sls_status : Acceptable, sls_utilisation : 94.13%, thickness : 145 mm, weight : 11.50 kg, width : 65 mm,

bending_status : Acceptable, bending_utilisation : 28.52%, buckling_status_in_plane : Acceptable, buckling_status_out_of_plane : Acceptable, buckling_utilisation_in_plane : 3.23%, buckling_utilisation_out_of_plane : 11.60%, compression_status : Acceptable, compression_utilisation : 2.97%, final_utilisation : 98.14%, final_utilisation_status : Acceptable, length : 2.00 m, shear_status : Acceptable, shear_utilisation : 20.62%, sls_status : Acceptable, sls_utilisation : 98.14%, thickness : 143 mm, weight : 11.34 kg, width : 65 mm,

bending_status : Unacceptable, bending_utilisation : 133.90%, buckling_status_in_plane : Acceptable, buckling_status_out_of_plane : Acceptable, buckling_utilisation_in_plane : 24.76%, buckling_utilisation_out_of_plane : 23.39%, compression_status : Acceptable, compression_utilisation : 6.33%, final_utilisation : 1013.75%, final_utilisation_status : Unacceptable, length : 2.00 m, shear_status : Acceptable, shear_utilisation : 44.00%, sls_status : Unacceptable, sls_utilisation : 1013.75%, thickness : 65 mm, weight : 5.31 kg, width : 67 mm,

bending_status : Unacceptable, bending_utilisation : 142.54%, buckling_status_in_plane : Acceptable, buckling_status_out_of_plane : Acceptable, buckling_utilisation_in_plane : 27.09%, buckling_utilisation_out_of_plane : 24.13%, compression_status : Acceptable, compression_utilisation : 6.53%, final_utilisation : 1113.40%, final_utilisation_status : Unacceptable, length : 2.00 m, shear_status : Acceptable, shear_utilisation : 45.40%, sls_status : Unacceptable, sls_utilisation : 1113.40%, thickness : 63 mm, weight : 5.15 kg, width : 67 mm,

bending_status : Unacceptable, bending_utilisation : 152.04%, buckling_status_in_plane : Acceptable, buckling_status_out_of_plane : Acceptable, buckling_utilisation_in_plane : 29.74%, buckling_utilisation_out_of_plane : 24.92%, compression_status : Acceptable, compression_utilisation : 6.74%, final_utilisation : 1226.54%, final_utilisation_status : Unacceptable, length : 2.00 m, shear_status : Acceptable, shear_utilisation : 46.89%, sls_status : Unacceptable, sls_utilisation : 1226.54%, thickness : 61 mm, weight : 4.99 kg, width : 67 mm,

Figure 4.8: cross-sectional options generated by iteration

Currently, Lock n Load features a weight optimization tool, similar to the one developed in the case study. This tool generates a variety of cross-sectional options for structural elements, each with its corresponding utilization factors for bending, shear, buckling, compression, and deflection, along with its respective weight. This allows users to assess the structural performance of various cross-sections while considering their weight. By providing these key performance indicators, the tool enables users to make informed decisions about the optimal cross-section for their design, balancing structural efficiency with weight minimization.

Lock n Load is designed to be adaptable to a wide range of user preferences and design approaches. By offering both manual input and automated optimization capabilities, it caters to

users with varying levels of expertise and different design philosophies. This flexibility empowers users to tailor the structural design process to their specific needs.

For instance, experienced engineers who prefer hands-on control can directly input their chosen dimensions for each structural element. Conversely, users who seek efficiency or wish to explore optimal solutions can utilize the automated optimization feature to determine the most efficient dimensions based on predefined constraints and loading conditions. This dual approach ensures that Lock n Load remains a versatile and accessible tool for a broad user base.

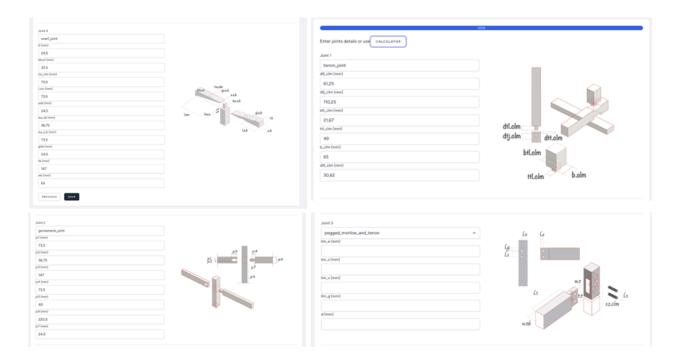


Figure 4.9: joint detail inputs

After determining the cross-sectional dimensions of the structural elements, the next stage in Lock n Load involves defining the connections between them. The system currently offers four families of joint types for users to choose from, providing a range of established connection design methods (figure 4.9).

However, recognizing the need for flexibility and customization, Lock n Load also allows expert users to define new joint types and integrate their own analytical methods through a dedicated API. This feature empowers users to expand the system's capabilities by incorporating specialized or innovative connection design approaches, making them accessible to other designers.

This thesis demonstrates this functionality by incorporating the "equivalent steel bolt" method for the design and optimization of PMT joints, developed gooseneck joint method, and scarf joint. Furthermore, a material-specific method was developed and implemented specifically for Douglas Fir timber. This exemplifies how Lock n Load can be extended to accommodate diverse joint design methodologies and cater to the specific requirements of different materials.



Figure 4.10: API Input panel for developing methods

Once all the geometric details for each of the four joints within the structural frame have been specified, Lock n Load generates a comprehensive report detailing both the structural performance and design specifics (figure 4.11). This report is structured in "**design blocks**", each providing a detailed breakdown of the individual components: beams, columns, tie beams, and joints. Within each block, users can find information on the chosen dimensions, materials, and connection details, along with an assessment of the element's structural performance, including utilization factors and deflections. Furthermore, the report provides an overall assessment of the entire structure's performance, considering the combined effects of all

elements and the specific loading conditions at the design location. This holistic evaluation allows users to verify the adequacy of their design and ensure it meets all safety and serviceability requirements. This output is then saved as a distinct design block within the design library, making it readily available for future reference.



Figure 4.11: data set in one block of design

Timber and CNC Provider

Lock n Load incorporates the crucial role of timber providers in the construction process by allowing them to actively participate in the platform. Timber providers can register on the system and create a "supply point" by specifying their location on a map (figure 4.12). They can also indicate their delivery radius, specifying how far they are willing to transport timber to CNC fabricators. This information is then displayed to shelter-seekers, enabling them to choose a provider based on proximity and availability. Furthermore, timber providers can specify the types of timber they currently have in stock from the material library. To ensure accuracy, they can access a database of timber properties to verify the characteristics of their stock. This material selection feature plays a crucial role in matching shelter-seekers with suitable shelter designs based on the locally available timber. This localized approach promotes resource efficiency and reduces transportation costs and environmental impact.

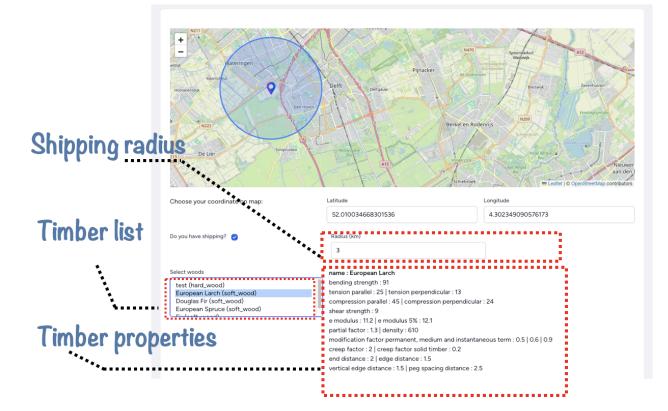
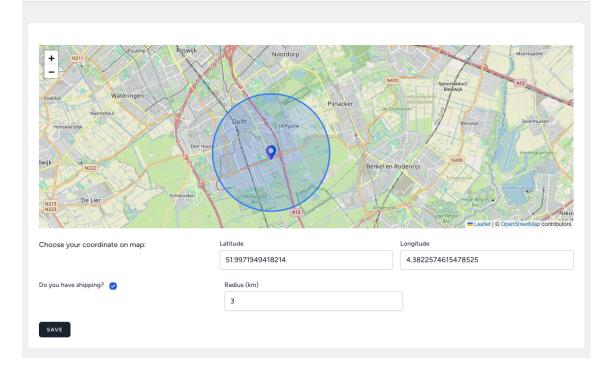


Figure 4.12: timber supplier panel

In the Lock n Load workflow, after timber is sourced from a provider, it is shipped to a CNC fabricator for cutting and fabrication of the structural elements. Similar to timber providers, CNC fabricators can register on the platform and specify their location, enabling the calculation of transportation distances for both timber providers and shelter-seekers (figure 4.12). This location information is crucial for several reasons:

- Efficient logistics: Timber providers can determine the shipping distance to various CNC fabricators, facilitating efficient logistics.
- Accessibility for shelter-seekers: Shelter-seekers can identify CNC fabricators within a reasonable distance for receiving their ready-to-assemble structural components. CNC providers can also specify their delivery radius for these finished elements.
- Localized supply chain: By connecting shelter-seekers with local timber providers and CNC fabricators, Lock n Load promotes a localized and sustainable supply chain, minimizing transportation distances and associated costs and environmental impact.



Create CNC Supply Point

Figure 4.13: CNC supplier panel

This system ensures a streamlined and transparent process, connecting all stakeholders and facilitating efficient collaboration between timber providers, CNC fabricators, and shelter-seekers.

Shelter-Seekers panel

Lock n Load streamlines the process of obtaining a customized timber shelter by guiding shelter-seekers through a series of steps. Upon entering the shelter-seeker panel, users are prompted to define their desired shelter dimensions (maximum and minimum height, width, and length). This customization allows for shelters tailored to individual needs and facilitates the selection of suitable designs from the available options (figure 4.14).

Shelter-seekers



Figure 4.14: size inputs from shelter-seekers

Next, shelter-seekers specify their location on a map. This triggers the "load verifier" tool, which analyzes the structural design library database and environmental load data to identify shelter designs capable of withstanding the specific conditions at that location (figure 4.15).

The filtered designs are then presented to the user, who can proceed to select a timber provider and the desired timber species. This further refines the available options, ensuring that the chosen shelter can be constructed using locally sourced materials. Subsequently, shelter-seekers can select a CNC fabricator based on proximity and delivery radius to ensure efficient processing and delivery of the prefabricated components (figure 4.16).

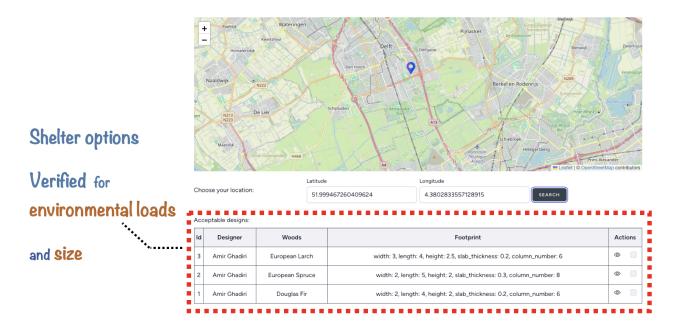


Figure 4.15: filtered design blocks based on environmental loads and sizing constraints

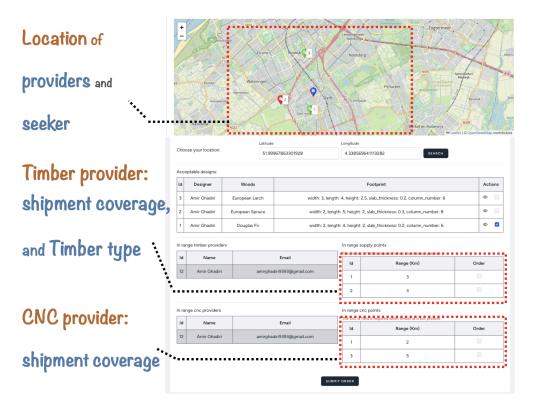


Figure 4.16: CNC and timber provider selection inputs

Once the order is submitted, Lock n Load automatically generates the necessary G-code instructions for the CNC fabrication process and sends them to the chosen provider. Simultaneously, the timber provider receives an order for the required timber, initiating the material supply chain. This automated workflow ensures seamless coordination between all stakeholders and facilitates the efficient delivery of customized timber shelters (figure 4.17).

G code generation



G21 G17 G90 F1000 S10000 G0 Z10 G0 X4.0 Y4.0 G1 Z-2 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-4 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-6 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-8 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-10 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-12 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-14 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-16 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-18 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-20 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-22 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-24 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-26 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-28 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-30 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-32 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-34 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-36 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-38 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-40 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-42 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-44 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-46 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-48 G1 X61 0 G1 Y216 5 G1 X4 0 G1 Y4 0 G0 Z10 G0 X4 0 Y4 0 G1 Z-50 G1 X61 0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-52 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-54 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-56 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-58 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-60 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-62 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-64 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-66 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-68 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-70 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-72 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-74 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-76 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-78 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-80 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-82 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-84 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-86 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1 Z-88 G1 X61.0 G1 Y216.5 G1 X4.0 G1 Y4.0 G0 Z10 G0 X4.0 Y4.0 G1

Figure 4.17: G-code generated and sent to CNC-provider order box

How Lock n Load Works: The Technical Details

Lock n Load employs a scalable web development architecture, utilizing **Laravel** for its **backend** framework and **JavaScript** for its **front-end** development. Specifically, **PHP** is used as the programming language for developing the backend within the Laravel framework.

To ensure a well-organized and maintainable codebase, the **Model-View-Controller (MVC) architectural pattern** is employed. This pattern separates the application into three interconnected components:

- Model: Handles data logic and interaction with the database.
- View: Manages the presentation layer and user interface.
- **Controller:** Acts as an intermediary between the Model and View, handling user requests and business logic.

This separation of concerns offers several advantages:

- Improved code organization: MVC promotes a clear and structured codebase, making it easier to understand, navigate, and maintain.
- Enhanced testability: Individual components (models, views, and controllers) can be tested independently, facilitating thorough testing and debugging.
- Increased scalability and extensibility: The modular nature of MVC simplifies the process of adding new features or modifying existing ones, enhancing the platform's scalability and adaptability to future needs.

By leveraging the Laravel framework and adhering to the MVC pattern, Lock n Load benefits from a robust and well-structured foundation, ensuring its maintainability, scalability, and future-proofing.

While Laravel and JavaScript provide the foundation for the web application, **Python** plays a crucial role in powering the core structural design and analysis capabilities.

Specifically, Python is used to develop and implement the structural design methods and perform the necessary computations. This includes algorithms for:

- **Structural analysis:** Calculating stresses, deflections, and other critical performance parameters.
- **Optimization:** Determining optimal cross-sectional dimensions and joint configurations.
- Load verification: Assessing the structural adequacy of designs under specific loading conditions.
- **G-code generation:** Generating CNC fabrication instructions.

To seamlessly integrate these Python-based functionalities into the web platform, a dedicated **API** was developed using **Flask**, a lightweight Python web framework. This **API** allows the Laravel backend to communicate with the Python modules, enabling efficient data exchange and execution of the structural design processes.

Backend framework of Lock n Load

The backend of Lock n Load is built on a robust and versatile architecture, primarily utilizing PHP within the Laravel framework. To manage user data and interactions, a **CRUD** (Create, Read, Update, Delete) system was implemented in **PHP**, enabling efficient handling of user information within the database. However, for certain functionalities, such as displaying material properties from the database, **jQuery** is employed to enhance the user interface and data presentation.

The design process within Lock n Load involves multiple layers, including footprint definition, cross-section selection, and joint design. To manage this **multi-step process**, design data is temporarily stored in a session rather than being immediately saved to the database. This approach ensures data integrity and allows for modifications throughout the design process until the finalization stage. The session mechanism, alongside managing user login data, also securely stores this temporary design information.

For location-based functionalities, Lock n Load integrates **OpenStreetMap**. The **JavaScript API** provided by OpenStreetMap enables the retrieval of various geographical data, including latitude and longitude coordinates, which are crucial for determining user location, provider proximity, and transportation distances.

Integration with the **Python-based** structural analysis modules is achieved through a dedicated **API** developed using **Flask**. When specific Python functionalities are required, such as structural calculations or G-code generation, the Laravel backend communicates with the Flask API via **POST requests**. These requests include validated input data, and the API returns a **JSON** response containing the results ("**print value**" and "**value**") as depicted in Figure 4.18. Error handling is implemented to ensure data integrity, with the API returning a non-200 OK status code in case of invalid input.

X Headers Payload	Preview Response Initiator Timing
▼ General	
Request URL:	http://127.0.0.1:5000/cross_section
Request Method:	POST
Status Code:	🔵 200 ОК
Remote Address:	127.0.0.1:5000
Referrer Policy:	strict-origin-when-cross-origin
▼ Response Headers	
	Raw
Access-Control-Allow-Origin:	http://127.0.0.1:8000
Connection:	close
Content-Length:	10893
Content-Type:	application/json
Date:	Sat, 26 Oct 2024 16:05:34 GMT
Server:	Werkzeug/3.0.4 Python/3.12.4
Vary:	Origin
▼ Request Headers	
	Raw
Accept:	application/json
Accept-Encoding:	gzip, deflate, br, zstd
Accept-Language:	en-US,en;q=0.9,fa-IR;q=0.8,fa;q=0.7
Connection:	keep-alive

Figure 4.18: API communication panel with Flask URL

To facilitate the selection of suitable providers, Lock n Load utilizes **jQuery** to send shelter-seeker location data to the CNC and timber provider APIs. This enables the system to filter and display providers whose shipment radius covers the seeker's location, as illustrated in figure 4.19. This dynamic filtering ensures that users are presented with relevant and accessible options for material supply and fabrication.

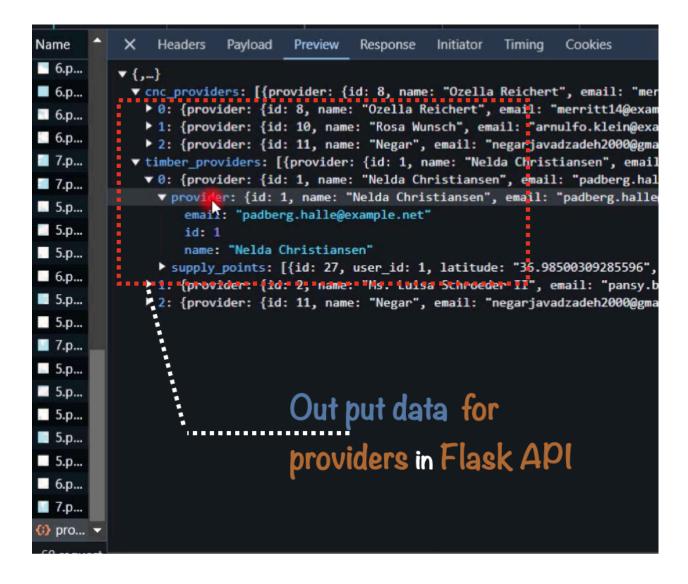


Figure 4.19: Output providers ID form FLASK API

Load Calculator

To automate the process of load combination alongside the values and factors mentioned above, load combinations according to Eurocode also include five components of the characteristic load value: **snow**, **wind**, **dead**, **seismic**, and **live** actions. However, in this tool, seismic loads are not covered, though it is recommended that they be considered in the future development. To calculate wind action, three main functions were defined: **wind pressure calculator**, the **peak wind velocity pressure calculator**, and the **wind load calculator on elements**. The peak wind velocity calculator includes several sub-functions that compute necessary values and factors which are: **Turbulence Intensity** (*Iv*), **Turbulence factor** (*kI*), **Terrain factor** (*kr*), **Roughness factor** (*cr*), **Roughness Length** (*z0*). **The fundamental value of the basic wind velocity (vb.0**), which is location-specific, is obtained from external online sources (as of the time of writing this thesis, © 2001–2024 Dlubal Software GmbH). The wind pressure calculator computes the wind pressure on the external surfaces of the shelter (*we*) by multiplying the peak wind velocity by the external pressure coefficient for the five different wind action zones defined in EN-1991-1-4.

The mechanism of calculating three actions of snow, live, and dead actions are similar. First the total effect of these actions is calculated on the shelter, then based on the vertical or horizontal nature of the elements the computing for load distribution is done. To calculate the snow load, the primary required value is the **characteristic snow load** (s_g). This value is multiplied by the snow load **shape coefficient**, **exposure coefficient**, and **thermal coefficient**, which are constant in our case due to the flat-roofed timber structure. To calculate the dead and live loads, the slab thickness must be specified by the users, and the timber density is obtained from the material database. For the live load calculation, Category A for floors with an area load (q_k) of 1.5 kN/m² is considered.

The calculator is developed in python (appendix), and defines several functions to calculate different types of loads on a structure according to Eurocode standards. Here's a breakdown of each function:

- peak_wind_velocity_calculator: This function calculates the peak wind velocity pressure based on parameters like basic wind velocity, height above ground, terrain factor, and turbulence factors, as defined in EN 1991-1-4. It calculates the mean wind velocity and turbulence intensity before ultimately determining the peak wind velocity pressure.
- wind_pressure_calculator: This function calculates the wind pressure on external surfaces using the peak wind velocity pressure and external pressure coefficients from EN 1991-1-4.
- **wind_load_on_elements:** This function calculates the wind load on individual structural elements by multiplying the wind pressure with the element's area.
- **snow_load:** This function calculates the snow load on a flat roof based on the characteristic ground snow load and various coefficients from EN 1991-1-3.
- dead_load: This function calculates the dead load of a structural element based on its material density, thickness, and area.
- live_load: This function calculates the live load on a floor using the specified area load and the floor area.

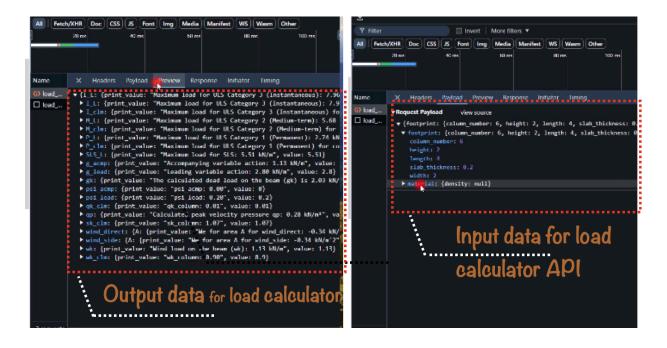


Figure 4.20: Output providers ID form FLASK API

Integration with Lock n Load:

This Python code is integrated with the Lock n Load platform through a Flask API. When a user inputs design parameters and location information, the Laravel backend sends a request to the Flask API, which executes the relevant Python functions to calculate the loads. The results are then returned to the backend in JSON format, allowing the platform to display the load values and proceed with the structural design process (figure 4.20).

Automated G-code Generation for CNC Milling of "Lock n Load" Joints

This section details the development of a Python-based (appandix) G-code generator for PMT joints and tie beams, however the G-CODE generator does not provide G-codes for other elements. For the PMT joint, a secure woodworking joint characterized by a through mortise, a mating tenon, and perpendicular peg holes for reinforcement. The generator aims to automate the CNC milling process for this joint, enhancing precision and efficiency in fabrication.

Joint Design and Parameters

The "Lock n Load" joint, as illustrated in the accompanying diagram, consists of:

- Mortise: A rectangular cavity that passes entirely through the first workpiece.
- **Tenon:** A protruding rectangular section on the second workpiece, sized to fit snugly into the mortise.
- **Peg holes:** Two perpendicular holes drilled through both the mortise and tenon, accommodating cylindrical pegs for added strength and stability.

The Python script allows for customization of the following parameters:

- Mortise: Width, height, and depth.
- **Tenon:** Width, height, and length.
- **Peg holes:** Diameter and depth.
- Milling: Tool diameter, feed rate, spindle speed, and step-down depth per pass.

G-code Generation Algorithm

The Python script employs a modular approach, defining functions for key milling operations:

- **mill_pocket():** Generates G-code for milling rectangular pockets, incorporating multiple passes with a specified step-down depth to ensure complete material removal.
- **drill_hole():** Generates G-code for drilling holes, with the option to include drilling cycles (e.g., G81) if supported by the CNC machine.

The main G-code generation function orchestrates these operations, first milling the mortise and tenon pockets, then drilling the peg holes through both workpieces. The generated G-code adheres to standard conventions, including:

- **G21:** Units in millimeters.
- **G17:** XY plane selection.
- **G90:** Absolute coordinates.
- F: Feed rate specification.
- **S:** Spindle speed specification.

Assumptions and Limitations

The current implementation operates under these assumptions:

- Workpiece origin (X0, Y0, Z0) is set at the top-left corner.
- A flat end mill is used for milling operations.
- The CNC machine has a safe Z clearance height defined.
- Basic G-code commands and potentially drilling cycles are supported.

Limitations include:

- Simplified toolpath strategies.
- No optimization for tool changes or material properties.
- Reliance on consistent workpiece setup and fixturing.

ASSUMPTION:

The workpiece origin (X0, Y0, Z0) is set at the top-left corner of the workpiece.

- The tool is a flat end mill suitable for cutting the workpiece material.
- The CNC machine has a safe Z clearance height for rapid moves.
- The machine supports basic G-code commands and potentially drilling cycles (e.g., G81).
- **Single Pass:** The mill_rectangle function only makes a single pass around the perimeter of the mortise and tenon. This would leave a lot of material in the middle. You would need multiple passes with progressively deeper cuts or a wider tool to fully clear the material.
- **No Pockets:** It doesn't account for creating the actual "pocket" of the mortise. It just cuts a shallow perimeter. Proper milling would involve clearing out the entire area within the mortise.
- **Drilling Only:** The drill_hole function only drills straight down. To create proper peg holes, you'd likely need to use a drilling cycle (like a G81 or similar) that handles pecking or retracting to clear chips.

Structural Optimizer and verifier

The weight optimization module in Lock n Load aims to provide users with the most weight-efficient cross-sections for their structural elements while ensuring that all design requirements are met. This is achieved through an evaluation of a range of possible cross-sectional dimensions, considering various load cases and design code provisions. Python code can be found in the appendix.

Workflow:

1. **Input Parameters:** The optimizer takes as input the material properties (strength, modulus of elasticity, density, etc.), loading conditions (forces, moments, etc.), and geometric constraints (length of the element). These parameters can either be user-defined or automatically retrieved from previous design steps within Lock n Load.

- 2. **Dimension Iteration:** The code iterates through a predefined range of widths and thicknesses for the cross-section. For each combination, it calculates the cross-sectional properties such as area, moment of inertia, and section modulus.
- 3. **Structural Analysis:** For each cross-section, the code performs structural analysis checks according to Eurocode 5:
 - **Bending Stress:** Calculates the maximum bending stress and compares it to the allowable bending strength of the material.
 - **Shear Stress:** Calculates the maximum shear stress and compares it to the allowable shear strength.
 - **Deflection:** Calculates the instantaneous and final deflections and compares them to the allowable limits for serviceability limit states (SLS).
 - **Compression:** Calculates the compressive stress and compares it to the allowable compressive strength.
 - **Buckling:** Checks for buckling failure in both the major and minor axes of the column, considering the slenderness ratio and instability factors.
- 4. **Utilization Calculation:** For each check, a utilization factor is calculated as the ratio of the applied stress/deflection to the allowable stress/deflection. This provides a measure of how much of the element's capacity is being utilized.
- 5. Acceptability Check: The code verifies whether each utilization factor is less than 100%. If any check fails, the cross-section is deemed unacceptable.
- 6. **Weight Calculation:** The weight of the element is calculated based on its volume and material density.
- 7. **Result Compilation:** The results, including weight, dimensions, utilization factors, and status (acceptable/unacceptable), are compiled for all considered cross-sections.

8. **Output:** The results are sorted by weight and presented to the user. This allows the user to select the lightest cross-section that satisfies all design requirements.

Code Structure and integration with Flask API:

The provided Python code effectively implements this workflow. It defines functions for calculating various loads, stresses, and utilization factors. The main function iterates through the dimensions, performs the structural analysis, and compiles the results.

The Python code for weight optimization in Lock n Load is seamlessly integrated into the platform through a combination of API endpoints and data exchange mechanisms. This integration allows the web application, built with Laravel and JavaScript, to leverage the computational power of Python for structural analysis and optimization (figure 4.21).

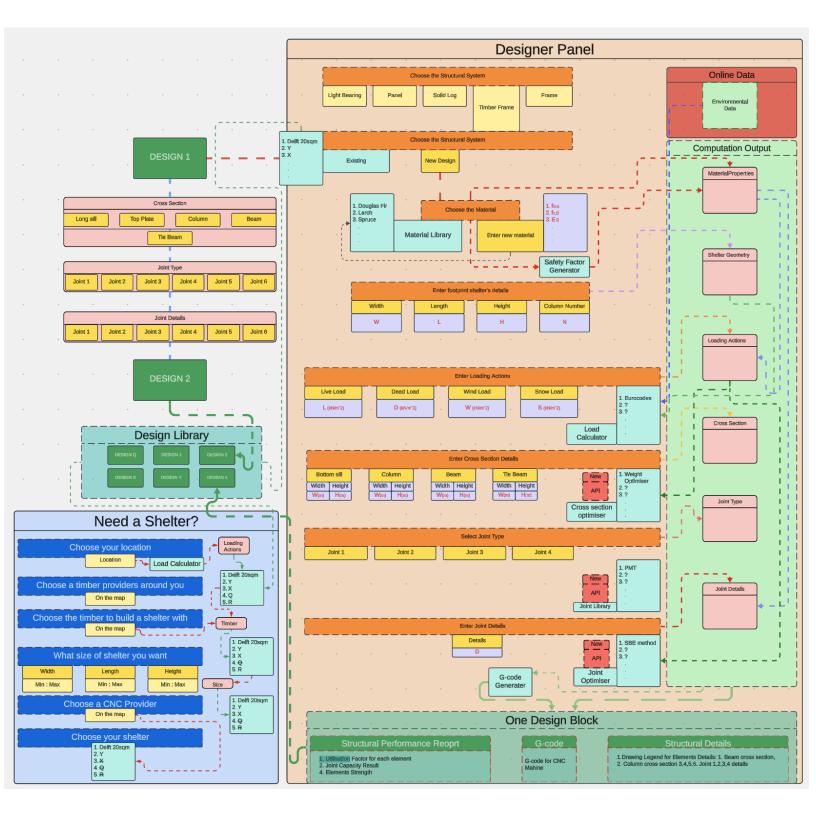


Figure 4.21: Output for structural verifier form FLASK API

Here's a breakdown of the integration process:

- 1. **Flask API:** The Python code, including the optimization algorithms and structural analysis functions, is exposed as a RESTful API using Flask, a lightweight Python web framework. This API defines specific endpoints that can be accessed by the Lock n Load backend.
- 2. **API Endpoints:** Each endpoint corresponds to a specific functionality, such as calculating loads, performing structural checks, or running the optimization algorithm. These endpoints accept input data in JSON format, which includes parameters like material properties, loading conditions, and geometric constraints.
- 3. **Request Handling:** When a user initiates the weight optimization process within the Lock n Load web interface, the JavaScript frontend sends an API request to the Flask backend. This request contains the necessary input data for the optimization process.
- 4. **Data Processing:** The Flask API receives the request, parses the JSON data, and executes the corresponding Python code. This involves running the optimization algorithm, performing structural analysis checks, and calculating utilization factors.
- Response Generation: Once the calculations are complete, the Flask API generates a JSON response containing the optimization results. This includes the optimized cross-section dimensions, weight, utilization factors, and status (acceptable/unacceptable).
- 6. **Data Exchange:** The JSON response is sent back to the Laravel backend, which then processes the data and displays it to the user in a user-friendly format within the web interface.
- 7. **Visualization and User Interaction:** The frontend utilizes JavaScript to visualize the optimization results, potentially through graphs, tables, or interactive displays. Users can then interact with these visualizations, explore different options, and make informed decisions about their design.

User Input/Output Flow



Conclusion and Future Recommendation

This research explored the development of "Lock n Load," a digital tool designed to revolutionize post-disaster timber shelter delivery. The core research question asked whether such a tool could simplify, improve, and integrate the processes of design, optimization, assembly, and delivery of these shelters, benefiting disaster victims, designers, and the entire supply chain. This research conclusively demonstrates that the answer is a resounding **yes**.

Lock n Load empowers **shelter designers** through dynamic, in-built features. Automated structural optimization, connection design tools, load calculators, and an extensive design library streamline the design process. Furthermore, an API allows **experts** to contribute to an evolving ecosystem of design methods, fostering ongoing innovation and refinement within the platform. The result is a more efficient workflow and a chain of continuous improvement in shelter design.

For those **seeking shelter**, Lock n Load dramatically **simplifies** the process. By answering a few basic questions about their needs and location, individuals can submit an order for a safe, customized, and readily obtainable shelter. This ease of access ensures that critical needs are met **quickly** and **efficiently** in the aftermath of a disaster.

The benefits extend throughout the **supply chain**. Lock n Load seamlessly **connects** designers and shelter seekers with timber providers and CNC fabricators. Orders and fabrication instructions are transmitted digitally, eliminating the need for direct communication between parties and ensuring a **smooth** and **coordinated flow** of materials and production.

The key to Lock n Load's success lies in its **web-based** platform. By leveraging the **accessibility** and **interconnected** nature of the internet, the tool unites all stakeholders within a single, **user-friendly** environment. This online foundation facilitates **seamless interaction** and information exchange, creating a dynamic and responsive system. Moreover, it positions Lock n Load for **future development, expansion**, and **adaptation** to evolving needs and technological advancements.

Research Limitations

1. While Lock n Load effectively addresses structural considerations, it currently lacks comprehensive integration of climate responsiveness and other crucial contextual factors. Although this limitation falls outside the initial scope of the research, the inherent challenge of merging climate-sensitive design with structural optimization necessitates a more sophisticated, multi-objective approach. Developing a linear framework that seamlessly considers both aspects presents a significant hurdle in achieving truly holistic and optimized shelter designs.

Future Recommendation:

To overcome this limitation, future development should prioritize the integration of climate-responsive design principles within Lock n Load. This could involve:

- **Developing a climate data integration module:** This module would allow users to input specific location data (e.g., temperature, humidity, rainfall, wind patterns) and receive design recommendations that optimize shelter performance in those conditions.
- Expanding the material library with climate-specific options: Including materials with varying thermal properties, moisture resistance, and durability would allow for tailored solutions based on climate considerations.
- Incorporating passive design strategies: The tool could suggest design features that maximize natural ventilation, solar gain, and shading to improve thermal comfort and reduce energy consumption.
- **Developing a "climate-responsive design score**": This score would evaluate the overall climate performance of a shelter design, helping users understand and optimize its suitability for the intended environment.
- **2.** Lock n Load currently restricts the addition of new structural systems and design methods to the administrator. This centralized control limits the platform's flexibility and

scalability, potentially hindering the rapid expansion and diversification of available shelter designs. Relying solely on administrator input creates a bottleneck and may not fully leverage the collective expertise of the broader engineering community.

Future Recommendation:

To address this, Lock n Load should evolve into a parametric platform that empowers users to define and contribute their own structural systems and design methods. This could be achieved by:

- Integrating parametric modeling tools: Allowing users to create parametric models of their structural systems would enable greater design flexibility and optimization.
- Developing a user-friendly interface for defining structural systems: This interface would allow users to input parameters such as materials, geometry, connections, and loading conditions to create custom structural systems
- **3.** Lock n Load currently lacks direct integration with Finite Element Analysis (FEA) software. This limits the platform's ability to perform detailed structural analysis and optimization, potentially leading to conservative designs or requiring users to rely on external FEA tools, disrupting the streamlined workflow.

Future Recommendation:

- Automate FEA simulations: The integration could automate the process of generating FEA models from Lock n Load designs, significantly reducing the time and expertise required for analysis.
- Offer varying levels of FEA fidelity: Provide options for different levels of analysis detail, allowing users to balance accuracy with computational cost depending on their needs.

4. Lock n Load currently lacks a robust system for comparing and evaluating the advantages of different design methods. This makes it difficult for designers to objectively assess which approach is best suited for a particular context. This limitation stems from the inherent subjectivity and complexity of timber structure design, particularly in joinery and timber framing, where numerous factors influence optimal solutions.

Future Recommendation:

- Developing a standardized set of performance metrics: These metrics could include structural efficiency, material usage, cost, construction time, environmental impact, and aesthetic considerations.
- Creating a comparative analysis tool: This tool would allow designers to input design parameters and receive a comparative analysis of different methods based on the chosen metrics.
- Incorporating a weighting system: Allow designers to assign weights to different performance metrics based on their priorities, generating customized rankings of design methods.
- Developing a visual comparison tool: Generate visual representations of different design options, highlighting key differences and trade-offs.

Reflection

Relation between my Graduation Project Topic and Building Technology

Building technology, as its name implies, serves as a crucial bridge between technology and architecture, introducing innovative methods and possibilities within the architectural domain. My graduation project embodies this same spirit, forging a connection between the tradition of timber construction and a novel digital tool aimed at its enhancement. This endeavor has allowed me to apply a range of skills and methodologies acquired during my studies in Building Technology, including structural design, material science, simulation, coding, and programming.

Influence of Research on Design/Recommendations and Vice Versa

Although I have always been an advocate of incorporating timber in design, my thesis project highlighted the complexities of utilizing timber as a structural material. The extensive research I conducted, ranging from examining the work of traditional carpenters to modern structural engineers, revealed that while timber is an intriguing and versatile material, it also presents significant challenges. This realization profoundly influenced my design approach, prompting me to adhere to the inherent limitations of timber and embrace the simplicity of traditional construction methods. This is evident in my thesis through the deliberate choice to employ a classic timber frame system, rather than adopting the more futuristic and intricate interlocking systems that are currently trending in timber design.

Assessment of the Value of the Way of Working (approach, used methods, used methodology)?

This thesis did not follow a single, straightforward methodology. Initially, I was somewhat lost, focusing solely on timber connections as the most interesting aspect for me. This narrow focus prevented me from adequately addressing the research questions I had defined. Consequently, I had to postpone my graduation. During the extended time, I embarked on a new path, engaging in a broader literature review and conducting a case study. This revised approach proved beneficial to the project, allowing me to design the foundation of the tool based on the case study findings. Developing "Lock n Load" grounded in a real structural design experience gave me a clearer understanding of the design process itself. With this clarity, I could then concentrate my efforts on automating this process.

How do you assess the academic and societal value, scope and implication of your graduation project, including ethical aspects?

The academic value of my project lies primarily in its novel approach to simplifying the provision of emergency shelter for everyone involved in the supply chain, not just the shelter seekers themselves. Particular attention was given to streamlining the design process and integrating it seamlessly with the supply chain. Additionally, from a societal perspective, my thesis aims to empower individuals to actively participate in providing shelter to those in need. This is how "Lock n Load" fosters a sense of community and shared responsibility.

How do you assess the value of the transferability of your project results?

Considering that my primary focus in developing "Lock n Load" was to empower users to create their own designs and methods, I believe this project has at least attempted to establish a platform that encourages exploration and adaptability to various contexts. For instance, I see no reason why this shelter-providing platform, with appropriate modifications and considerations, couldn't be utilized for different types of structures in diverse situations. Furthermore, although the tool primarily focuses on structural optimization, I envision future projects adapting a similar approach to optimize other aspects of building design, such as environmental sustainability or social impact.

Personal Reflection

The most crucial soft skill I developed during this thesis was learning to aim for what's achievable. Initially, I was overly ambitious, envisioning a project that would encompass every possible aspect. This led to setbacks and ultimately, I had to postpone my graduation. Subsequently, I shifted my focus from creating a grand project to developing a genuinely useful one. I learned numerous techniques and skills throughout this thesis. Notably, structural design, which had previously been outside my comfort zone and not a strength of mine, became an area where I made significant progress. Initially, I struggled with some of the fundamental concepts, but I persevered and learned a great deal.

While I've always possessed strong coding skills, working on a project of this scale and with multiple coding languages involved truly solidified my confidence in my ability to code.

Additionally, I believe the most challenging aspect of this thesis was learning how to work with Finite Element Analysis software, specifically Ansys. This is a skill not typically taught in architecture schools, adding another layer of complexity to the project. Working with timber specifically made the FEM simulation process more challenging, as timber can exhibit less predictable behavior under various conditions. To address this issue, I had to seek out specialized literature focusing on specific types of timber. I believe the final results demonstrate a good validation performance.

Future research should focus on developing a tool that empowers users to define structural systems beyond the administrative constraints of the current site. This limitation arose from my limited expertise in web design, particularly in backend development. However, even small components of this project could be improved, particularly the non-structural aspects of the existing system.

Ultimately, I believe "Lock n Load" can address, or at least partially resolve, the problem statement raised at the outset. It has the potential to streamline the process of designing and delivering shelters, which was the primary objective of this project.

Appendix :

Matlab codes for optimisation of PMT

clc

clear

%% Reading the data

A = xlsread('Optimisation.xlsx');

v = linspace(0,10,size(A,1));

Force_index = 1:4:97;

Peg_index = 2:4:98;

Tenon_index = 3:4:99;

Mortise_index = 4:4:100;

F = A(:,Force_index);

sigma_Peg = A(:,Peg_index); sigma_Tenon = A(:,Tenon_index); sigma_Mortise = A(:,Mortise_index);

%% Finding the Yield Forces

N = 200;

x = linspace(0,8,N);

G = zeros(N,length(F));

X0 = zeros(1,length(F));

Y0 = zeros(1,length(F));

for i = 1:length(F)

```
m = (F(2,i)-F(1,i))/(v(2)-v(1));
```

G(:,i) = m*(x-0.5);

[X0(i),Y0(i)] = intersections(x,G(:,i),v,F(:,i));

end

%% Plots

figure

subplot(2,2,1)

plot(v,F/1000,'LineWidth',2)

xlabel('Deflection (mm)')

ylabel('Load (kN)')

grid on

set(gca,'Linewidth',2)

subplot(2,2,2)

plot(v,sigma_Peg;'LineWidth',2) xlabel('Deflection (mm)') ylabel('Max Stress in Peg (MPa)') grid on set(gca,'Linewidth',2)

subplot(2,2,3) plot(v,sigma_Tenon,'LineWidth',2) xlabel('Deflection (mm)') ylabel('Max Stress in Tenon (MPa)') grid on set(gca,'Linewidth',2)

subplot(2,2,4) plot(v,sigma_Mortise,'LineWidth',2) xlabel('Deflection (mm)') ylabel('Max Stress in Tenon (MPa)')

grid on

set(gca,'Linewidth',2)

plot(Y0/1000,'*') xlabel('Case Number')

ylabel('Yield Load (kN)')

grid on

grid minor

set(gca,'Linewidth',2)

plot(max(sigma_Tenon),'*')

xlabel('Case Number')

ylabel('Maximum Stress in Tenon (MPa)')

grid on

grid minor

set(gca,'Linewidth',2)

figure

plot(Y0/1000,max(sigma_Peg),'*') xlabel('Yield Load (kN)') ylabel('Maximum Stress in Peg (MPa)') grid on

set(gca,'Linewidth',2)

FEM optimisation loop results of PMT joints

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 | n (MPa) Max Stress in Morting
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Max Sizesi in Marin
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Force (N)	Max Stress in Peg (MPa)	Max Stress in Tenon (MPa)	Max Stress in Mortise (MPa)	Force (N)	Max Stress in Peg (MPa	Max Stress in Tenon (MPa)	Max Stress in Mortise (MPa)	Force (N)	Max Stress in Peg (MPa)	Max Stress in Tenon (MPa)	Max Stress in Mortise (M	Pa) Force (N)
0	0	0	0	0	0	0	0	0	0	0	0	0
4298,5 8545,9	4,8098 9,8372	15,389 31,229	6,362 10,945	4440,5	4,2315	14,423	5,5082	4342,6 8635,3	5,0281 10,406	14,507 29,489	5,8259 10,432	4415,1 8780,7
12723	11,357	41,875	14,95	13156	10.569	45.304	13,449	12853	11,822	45,07	15,147	13081
16742	13,715	46,548	19,383	17332	12,064	45,299	17,663	16909	13,879	45,701	19,01	17237
20553	15,764	40,56	23,944	21306	13,732	44,507	21,687	20730	15,914	54,434	23,271	21197
24124 27541	17,662 19,624	48,474	28,299 32,717	25056	15,584	46,662	25,472	24335 27789	18,019 20,242	45,89 53,05	27,615 32,084	24937 28545
30850	21,627	64,587	37,23	32228	19,665	62,312	32,673	31141	22,578	60,371	36,611	32079
34069	23,731	72,493	39,564	35724	21,773	69,721	36,164	34408	24,911	67,477	40,142	35556
37198	25,849	80,381	41,686	39169	23,88	77,065	37,381	37591	27,232	74,111	42,509	38984
40222 43126	27,983 30,122	88,153 95.625	44,444 48	42572	25,996	84,398	40,552	40682 43678	29,562 31,877	80,883 87,73	45,011 49,126	42369 45713
45951	32.238	102.93	51,214	49265	30.208	99.051	46,731	46598	34.16	94,264	52.289	49023
48711	34,317	110,1	53,811	52564	32,3	106,19	49,731	49453	36,408	100,68	55,119	52298
51411	36,356	117,19	56,066	55831	34,373	113,22	52,577	52248	38,624	106,87	57,493	55539
54065 56671	38,379 40,385	124,21 131,09	58,195 60,276	59067	36,426	120,14	55,185	54977 57643	40,796 42,939	112,78 118,54	59,633 61,66	58749 61925
59223	42,364	137,84	62,877	65444	40.507	133.64	54,836	60256	45,061	124,17	63,803	65065
61724	44,322	144,48	65,48	68573	42,526	140,33	57,05	62821	47,158	129,69	66,48	68156
64190	46,267	151,08	68,005	71652	44,515	146,99	59,859	65344	49,228	135,15	69,083	71196
Case 13				Case 14				Case 15				Case 16
Force (N)		Max Stress in Tenon (MPa)	Max Stress in Mortise (MPa)) Max Stress in Tenon (MPa)						Pa) Force (N
0 4415,1	0 4,1999	0 15,48	0 5,3726	0 4278,1	0 4,728	0 16.355	0 6,215	0 4414,7	0 4,2073	0 19,128	0 5,6343	4260.5
8780,7	8,5581	28,953	9,8165	8506,3	9,6717	33,049	11,454	8780,3	8,6556	32,275	10,364	8473.5
13081	9,9519	42,16	13,463	12656	11,288	42,491	15,601	13077	10,48	49,631	14,394	12560
17237	12,015	56,927	17,723	16645	13,643	49,474	18,799	17228	12,045	47,002	18,986	16445
21197 24937	13,686 15,498	52,408 47,7	21,772 25,584	20422 23966	15,645 17,576	42,043 49,752	23,107 27,275	21183 24915	13,699 15,548	47,322 45,973	21,876 25,682	20063
28545	15,498	55,825	29,25	23900	19,491	49,752 57,964	31,665	24915 28516	15,548	54,548	29,316	26776
32079	19,619	64,767	32,828	30623	21,492	65,797	36,2	32043	19,664	63,256	32,812	29988
35556	21,756	71,811	34,098	33805	23,553	73,539	40,019	35516	21,803	71,759	33,786	33114
38984 42369	23,913 26.075	79,86 87,961	37,321 40,49	36891 39856	25,63 27,736	81,192 88,722	41,965 46,217	38938 42319	23,935 26,071	80,096 88,373	37,142 39,054	36147
42369 45713	26,075 28,25	87,961 95,991	40,49 43,602	39856	27,736	88,722 96,089	46,217 50.7	42319 45660	26,071 28,226	88,373 96,381	39,054 41,889	41068
49023	30,401	103,94	46,667	45509	31,856	103,23	53,758	48966	30,374	104,16	44,594	44763
52298	32,525	111,77	49,68	48229	33,857	110,22	56,267	52240	32,507	111,88	47,219	47497
55539	34,623	119,51	52,58	50892	35,831	117,14	58,412	55483	34,62	119,56	49,768	50168
58749 61925	36,708 38,779	127,19 134,77	55,252 57,759	53504 56060	37,78 39,704	124,03 130,81	60,451 62,49	58694 61871	36,709 38,791	127,21 134,78	52,203 54,697	52774
65065	40,831	142,39	58,202	58564	41,606	137,48	64,536	65005	40,847	142,18	57,099	57823
68156	42,847	149,91	61,262	61024	43,562	144,04	66,591	68090	42,88	149,44	59,397	60276
71196	44,833	157,28	64,313	63445	45,495	150,51	69,171	71116	44,885	156,51	61,514	62688
Case 16				Case 17				Case 18				Case 19
										M. C. 17. (D)	Max Stress in Mortise (MI	
Force (N) 0	Max Stress in Peg (MPa) 0	Max Stress in Tenon (MPa) 0	Max Stress in Moruse (MPa) 0	Force (N) 0	0	Max Stress in Tenon (MPa) 0	Max Stress in Mortise (MPa) 0	Force (N) 0	Max Stress in Peg (MPa) 0	Max Stress in Tenon (MPa) 0	0	Pa) Force (N) 0
Force (N) 0 4260,5	Max Stress in Peg (MPa) 0 4,7943	0 14,875	0 6,2237	0 4337,7	0 5,6814	0 16,565	0 5,5006	0 4192,2	0 4,9294	0 15,97	0 6,2669	0 4391,1
Force (N) 0 4260,5 8473,5	Max Stress in Peg (MPa) 0 4,7943 9,999	0 14,875 30,441	Max Stress in Moruse (MPa) 0 6,2237 10,879	0 4337,7 8629,8	0 5,6814 11,37	0 16,565 33,115	0 5,5006 9,4999	0 4192,2 8333,7	0 4,9294 9,6702	0 15,97 32,411	0 6,2669 11,671	0 4391,1 8734,3
Force (N) 0 4260,5 8473,5 12560	Max Stress in Peg (MPa) 0 4,7943 9,999 11,53 13,664	Max Stress in Tenon (MPa) 0 14,875 30,441 46,332 47,966	0 6,2237 10,879 15,61	0 4337,7 8629,8 12805	0 5,6814 11,37 10,369	0 16,565 33,115 39,514	0 5,5006 9,4999 13,267	0 4192,2 8333,7 12353	0 4,9294 9,6702 11,377	0 15,97 32,411 44,702	0 6,2669 11,671 14,545	0 4391,1 8734,3 13007
Force (N) 0 4260,5 8473,5 12560 16445 20063	Max Stress in Peg (MPa) 0 4,7943 9,999 11,53 13,684 15,748	Max Stress in Lenon (MPa) 0 14,875 30,441 46,332 47,986 41,175	0 6,2237 10,879 15,61 19,441 23,912	0 4337,7 8629,8	0 5,6814 11,37	0 16,565 33,115	0 5,5006 9,4999	0 4192,2 8333,7	0 4,9294 9,6702	0 15,97 32,411	0 6,2669 11,671	0 4391,1 8734,3
Force (N) 0 4260,5 8473,5 12560 16445 20063 23479	15,748 17,797	49,06	28,431	0 4337,7 8629,8 12805 16790 20530 24060	0 5,6814 11,37 10,369 12,377 14,23 16,663	0 16,565 33,115 39,514 46,602 42,695 51,076	0 5,5006 9,4999 13,267 17,437 20,645 23,476	0 4192,2 8333,7 12353 16175 19731 23077	0 4,9294 9,6702 11,377 13,534 15,594 17,534	0 15.97 32,411 44,702 40,43 46,108 54,19	0 6,2669 11,571 14,545 18,668 22,94 27,347	0 4391,1 8734,3 13007 17136 21064 24773
Force (N) 0 4260.5 8473.5 12560 16445 20063 23479 26776 2000		Max stress in tenon (MPa) 0 14,875 30,441 46,332 47,986 41,175 49,06 57,495	Max Stress in Morrise (MPa) 0 6,2237 10,879 15,61 19,441 23,912 28,431 33,048	0 4337,7 8629,8 12805 16790 20530 24060 27498	0 5,6814 11,37 10,369 12,377 14,23 16,663 19,291	0 16,565 33,115 39,514 46,602 42,695 51,076 59,95	0 5,5006 9,4999 13,267 17,437 20,645 23,475 26,869	0 4192,2 8333,7 12353 16175 19731 23077 26294	0 4,9294 9,6702 11,377 13,534 15,594 17,534 19,547	0 15,97 32,411 44,702 40,43 46,108 54,19 62,787	0 6,2669 11,671 14,545 18,668 22,94 27,347 31,82	0 4391,1 8734,3 13007 17136 21064 24773 28352
Force (N) 0 4260,5 8473,5 12560 16445 20063 23479 26776 29988 33114	15,748 17,797	49,06	28,431	0 4337,7 8629,8 12805 16790 20530 24060 27498 30877	0 5,6814 11,37 10,369 12,377 14,23 16,663 19,291 22,009	0 16,565 33,115 39,514 46,602 42,695 51,076 59,95 68,382	0 5,5006 9,4999 13,267 17,437 20,645 23,476 26,869 30,186	0 4192,2 8333,7 12353 16175 19731 23077 26294 29418	0 4,9294 9,6702 11,377 13,534 15,594 17,534 19,547 21,633	0 15,97 32,411 44,702 40,43 46,108 54,19 62,787 71,294	0 6,2669 11,671 14,545 18,668 22,94 27,347 31,82 36,453	0 4391,1 8734,3 13007 17136 21064 24773 28352 31855
Force (N) 0 4260.5 8473.5 12560 16445 20063 23479 26776 29988 33114 36147	15,748 17,797	49,06	28,431	0 4337,7 8629,8 12805 16790 20530 24060 27498	0 5,6814 11,37 10,369 12,377 14,23 16,663 19,291 22,009 24,814	0 16,565 33,115 39,514 46,602 42,605 51,076 59,95 68,382 76,771	0 5,5006 9,4999 13,267 17,437 20,645 23,476 26,869 30,186 33,473	0 4192,2 8333,7 12353 16175 19731 23077 26294 29418 32450	0 4,9294 9,6702 11,377 13,534 15,594 17,534 19,547 21,633 23,779	0 15,97 32,411 44,702 40,43 46,108 54,19 62,787 71,294 79,315	0 6.2669 11.671 14.545 18.668 22.94 27.347 31.82 36.453 39.812	0 4391,1 8734,3 13007 17136 21064 24773 28352 31855 35303
Force (N) 0 4260.5 8473.5 12560 16445 20063 23479 26776 29988 33114 36147 39096	15,748 17,797	49,06	28,431	0 4337,7 8629,8 12805 16790 20530 24060 27498 30877 34204 37485 40728	0 5,6814 11,37 10,369 12,377 14,23 16,663 19,291 22,009 24,814 27,643 30,471	0 16,565 33,115 39,514 46,602 42,605 51,076 59,95 68,382 76,771 88,229 93,711	0 5,5006 9,4999 13,267 17,437 20,645 23,476 26,869 30,186 33,473 35,86 37,529	0 4192,2 8333,7 12353 16175 19731 23077 26294 29418 32450 35378 38213	0 4.9294 9,6702 11,377 13,534 15,594 17,534 19,547 21,633 23,779 25,963 28,155	0 15.97 32.411 44.702 40.43 46.108 54.19 62.787 71.294 79.315 87.208 94.963	0 6,2669 11,671 14,545 18,668 22,94 27,347 31,82 36,453 39,812 43,56 47,153	0 4391,1 8734,3 13007 17136 21064 24773 28352 31855 35303 38702 42058
Force (N) 0 4260,5 8473,5 12560 16445 20063 23479 26776 29988 33114 36147 39096 41968	15,748 17,797	49,06	28,431	0 4337,7 8629,8 12805 16790 20530 24060 27498 30877 34204 37485 40728 43934	0 5,6814 11,37 10,369 14,23 16,663 19,291 22,009 24,814 27,643 30,471 33,298	0 16,565 33,115 99,514 46,602 42,6095 51,076 59,95 66,382 76,771 88,322 93,711 101,99	0 5,5006 9,4099 13,267 17,437 20,645 23,476 26,869 30,186 33,473 35,86 37,529 40,452	0 4192,2 8333,7 12353 16175 19731 23077 26294 29418 32450 35378 38213 40964	0 4.9294 9.6702 11.377 13.534 15.594 19.547 21.633 23.779 25.963 28.155 30.312	0 15.97 32,411 44,702 40,43 46,108 54,19 62,787 71,294 87,208 94,963 102,51	0 6,2669 11,671 14,545 22,94 27,347 31,82 36,453 39,912 43,56 47,153 50,602	0 4391,1 8734,3 13007 17136 21064 24773 28352 31855 35303 38702 42058 45375
Force (N) 0 4260,5 8473,5 12560 16445 20063 23479 26776 29988 33114 36147 39096 41968 44763	15,748 17,797	49,06	28,431	0 4337,7 8629,8 12805 16790 20530 24060 27498 30877 34204 37485 40728 43934 47106	0 5,5814 11,37 10,369 12,377 14,23 16,663 19,291 22,009 24,814 27,643 30,471 33,298 36,092	0 16,565 33,115 39,514 46,602 42,695 51,076 59,95 68,382 76,771 85,229 93,711 101,99 110.16	0 5,5006 9,4099 13,267 17,437 20,645 23,476 26,869 30,186 33,473 35,86 37,529 40,452 43,214	0 4192,2 8333,7 12353 16175 19731 23077 26294 29418 32450 35378 38213 40964 43634	0 4.9294 9.6702 11.377 13.534 17.534 17.534 19.547 21.633 23.779 25.963 28.155 30.312 32.415	0 15.97 32,411 44,702 40,43 46,108 54,19 62,787 71,294 79,315 87,208 94,963 102,51 109,81	0 6,2669 11,671 14,545 22,94 27,347 31,82 36,653 39,812 43,56 47,153 50,602 54,212	0 4391,1 8734,3 13007 17136 21064 24773 28352 31855 35303 38702 42058 45375 48655
Force (N) 0 4260,5 8473,5 12560 16445 20063 23479 26776 29988 33114 36147 39096 41968 44763 47497	15,748 17,797	49,06	28,431	0 4337,7 8629,8 12805 16790 20530 24060 27498 30877 34204 37485 40728 43934 47106 50244	0 5,6814 11,37 10,369 12,377 14,23 16,663 19,291 22,009 24,814 27,643 30,471 33,298 36,092 38,868	0 16,565 33,115 46,602 42,605 51,076 59,05 66,382 76,771 88,229 93,711 101,99 110,16 118,44	0 5,5006 9,4999 13,267 17,437 20,645 23,476 26,869 30,186 33,473 35,86 37,529 40,452 43,214 45,91	0 4192,2 8333,7 12353 16175 19731 23077 26294 29418 32450 35378 38213 40964 43634 46239	0 4,9294 9,6702 11,377 13,534 15,594 17,534 19,547 21,633 23,779 25,963 28,155 30,312 32,415 33,464	0 1597 32,411 44,702 40,43 46,108 54,19 62,787 71,294 79,315 87,208 94,963 102,51 109,81 116,98	0 6,2669 11,671 14,545 18,665 22,94 27,347 31,82 36,453 39,812 43,36 47,153 50,602 54,212 56,93	0 4391,1 8734,3 13007 17136 21064 24773 28352 33855 35303 38702 42058 45375 48655 51904
Force (N) 0 4260,5 4260,5 12560 16445 20063 23479 26776 29988 33114 36147 39096 41968 44763 47497 50168	15,748 17,797	49,06	28,431	0 4337,7 8629,8 12805 16790 20530 24060 27498 30877 34204 37485 40728 43934 47106 50244 53350 56427	0 5,6814 11,37 10,369 12,377 14,23 16,663 19,291 22,009 24,814 27,643 30,471 33,298 36,092 38,868 41,615	0 16,565 33,115 42,695 42,695 53,95 64,382 64,382 64,382 64,382 93,711 101,99 93,711 101,99 110,16 118,44 126,56	0 5,5005 9,4099 13,267 17,437 20,045 23,476 30,495 30,495 30,495 33,565 37,529 40,052 43,214 45,91 48,514 51,12	0 4192,2 8333,7 12353 16175 19731 23077 26294 29418 32450 35378 38213 40964 43634 44639 48790 51289	0 4,9294 9,6702 11,377 13,534 15,594 19,547 21,633 23,779 25,563 28,155 30,312 32,415 34,464 36,479 38,464	0 1597 32,411 44,702 40,43 46,108 54,19 62,787 79,315 79,315 79,315 77,308 94,963 102,51 109,81 116,98 123,98 130,93	0 6,2669 11,671 14,545 18,665 22,04 27,347 31,82 36,453 39,812 43,36 47,153 50,602 54,212 56,03 59,138 61,186	0 4391,1 8734.3 13007 17136 21064 24773 28352 33855 35303 38702 42058 45375 48655 51904 55118 \$8297
Force (N) 0 4260,5 8473,5 12560 16445 20063 23479 26776 29988 33114 36147 30996 44763 44763 44763 447497 50168 52774 55322	15,748 17,797	49,06	28,431	0 4337,7 8629,8 12805 16790 20530 24060 27498 30877 34204 37485 40728 43934 43934 43934 45350 56427 56427	0 5,5814 11,37 10,369 12,377 14,23 16,663 19,291 22,009 24,814 27,643 30,471 33,298 36,092 38,868 41,6,15 44,334 47,019	0 16,565 33,115 44,662 42,695 59,95 68,382 76,771 88,229 99,711 101,99 110,16 118,41 126,56 134,66 142,23	0 5,5006 9,4099 11,3,67 20,464 23,475 23,475 20,686 30,086 33,473 35,86 37,529 44,0421 44,91 45,91	0 4192,2 8333,7 12353 16175 19731 23077 26294 29418 32450 35378 38213 40964 43634 46239 44634 46239 51289 51289	0 4,9294 9,6702 11,377 13,534 15,594 15,594 15,547 21,633 23,779 25,963 28,155 30,312 32,415 34,464 36,679 38,464	0 1597 32,411 44,702 40,43 46,108 54,19 62,787 71,294 79,315 87,208 94,963 102,51 109,81 116,98 123,98 133,98 133,76	0 6.2669 11.671 14.545 18.668 22,94 27,347 31.82 36,453 39,812 43,36 47,153 50,602 54,212 56,93 59,138 61,086 62,977	0 4391,1 8734,3 13007 17136 21064 24773 28352 31855 35303 38702 42058 45375 48655 51904 55118 55197 61435
Force (N) 0 4260,5 8473,5 12560 16445 20063 23479 26776 29988 33114 36147 39096 41968 44763 44763 44763 44763 44763 50168 52774 55322 57823 60276	15,748 17,797	49,06	28,431	0 4337,7 8629,8 12805 16790 20530 24060 27498 30877 34204 37485 40728 43934 47106 50244 53350 56427 59471	0 5,6814 11,37 10,369 12,377 14,23 16,663 19,201 22,009 22,009 23,843 30,471 33,298 36,092 38,868 44,615 44,334 44,058	0 16,565 33,115 42,605 51,076 53,05 64,332 64,332 64,332 64,332 93,711 10,19 110,16 118,41 112,556 1144,66 1142,83 150,84	0 5,5006 9,4099 13,267 17,437 20,045 23,476 30,165 33,167 33,175 33,167 33,175 33,167 33,175 33,167 33,175 33,167 33,167 33,167 33,167 33,167 33,167 33,167 33,167 33,167 34,175 34,	0 4192.2 8333,7 12353 16175 19731 23077 26294 29418 32450 35378 35378 35378 35378 35213 40964 43634 446239 48790 51289 53734 56130	0 4.9594 9.6702 11.377 13.534 13.534 19.541 23.179 23.179 23.179 25.663 25.663 25.663 23.2415 32.415 33.4464 36.479 38.464 40.462 42.457	0 1597 32,411 44,702 40,43 46,108 54,19 62,787 79,315 79,315 79,315 79,315 94,963 100,81 106,98 123,98 130,993 1337,76 144,51	0 6.2669 11.671 14.545 18.668 22.04 27.347 31.82 36.453 39.043 39.043 39.043 47.153 47.153 54.212 56.03 59.138 61.1086 62.977 64.846	0 4391,1 8734,3 13007 17136 22064 24773 28352 31855 31855 31857 348655 51904 42058 48655 51904 55118 58297 61435
Force (N) 0 4260,5 8473,5 12560 16445 20063 23479 26776 29988 33114 306147 39096 41968 44763 36147 39096 44763 52678 52774 53322 57823 60276 62688	15,748 17,797	49,06	28,431	0 4337,7 8629,8 12805 16790 20530 24060 27498 30877 34204 37485 40728 43934 43934 43934 45350 56427 56427	0 5,5814 11,37 10,369 12,377 14,23 16,663 19,291 22,009 24,814 27,643 30,471 33,298 36,092 38,868 41,6,15 44,334 47,019	0 16,565 33,115 44,662 42,695 59,95 68,382 76,771 88,229 99,711 101,99 110,16 118,41 126,56 134,66 142,23	0 5,5006 9,4099 11,3,67 20,464 23,475 23,475 20,686 30,086 33,473 35,86 37,529 44,0421 44,91 45,91	0 4192,2 8333,7 12353 16175 19731 23077 26294 29418 32450 35378 38213 40964 43634 46239 44539 51289 51289	0 4,9294 9,6702 11,377 13,534 15,594 15,594 15,547 21,633 23,779 25,963 28,155 30,312 32,415 34,464 36,679 38,464	0 1597 32,411 44,702 40,43 46,108 54,19 62,787 71,294 79,315 87,208 94,963 102,51 109,81 116,98 123,98 133,98 133,76	0 6.2669 11.671 14.545 18.668 22,94 27,347 31.82 36,453 39,812 43,36 47,153 50,602 54,212 56,93 59,138 61,086 62,977	0 4391,1 8734,3 13007 17136 21064 24773 28352 31855 35303 38702 42058 45375 48655 51904 55118 55194
Fonce (N) 0 0 4260,5 8473,5 12560 16445 20063 23479 26776 29988 33114 36147 36147 39096 41968 44763 44763 44763 55322 55323 55322 55323 55322 55323 55323 55323 55323 55322 55323 5532 55323 5532	15,748 17,797	49,06	28,431	0 4337,7 8629,8 12805 16790 20530 24060 27498 34204 37498 34204 37498 34204 37498 34204 37498 34204 37498 34204 37498 34204 37498 43934 47106 502476 502476 56427 59471 59471 59471 59471	0 5.6814 11.37 10.369 12.377 14.23 16.663 19.291 22.009 24.814 27.643 30.471 33.298 36.092 38.668 41.615 44.334 47.019 49.658 52.248	0 16,565 33,115 45,005 45,005 59,95 68,382 76,771 88,229 93,711 101,96 110,46 116,46116,46 116,465 116,465 116,465 116,465 116,	0 5,5006 9,4099 13,267 17,437 20,147 20,	0 4192,2 8333,7 12353 16175 19731 23077 26294 29418 32450 35378 38213 38213 38213 38213 40964 43634 46239 51289 5129 51289 5129 51289 51289 51289 51289 51289 51289 51289 51289 51289 51289 51289 51289 51289 51289 51289 51289 51289 51289 51289 5129 51289 51289 51289 51289 51289 51289 51289 51289 51289 51289 51289 51289 51289 51289 51289 5129 5129 51289 51289 5129 5129 5129 5129 5129 5129 5129 512	0 4,9294 9,6702 11,377 13,534 15,594 17,534 19,547 21,633 23,779 28,155 30,312 32,415 34,464 36,679 38,464 40,462 44,42	0 1597 32,411 44,902 46,108 46,109 46,109 46,109 47,109 71,294 73,215 87,208 94,963 102,51 109,81 113,98 113,98 133,76 144,51 151,2	0 6.2669 11.671 14.545 27.54 36.653 39.812 43.36 47.153 59.602 54.212 54.212 56.133 96.138 96.1086 61.086 64.846 66.698	0 4391,1,1 8734,3 13007 17136 21064 24773 38352 31855 35303 42058 45375 48655 51904 455118 58297 61435 5496 45518
Force (N) 0 4260.5 8473.5 12560 16445 2006.3 23479 26776 29988 33114 36147 30996 41968 41968 44763 30996 41968 44763 5322 57823 60276 60276 60288 Case 19	15,748 17,797	49,06	28,431	0 4337,7 8629,8 12805 16790 20530 24060 27498 30877 34204 37485 40728 43934 47106 50244 53350 56427 59471 62476	0 5.6814 11.37 10.369 12.377 14.23 16.663 19.291 22.009 24.814 27.643 30.471 33.298 36.092 38.668 41.615 44.334 47.019 49.658 52.248	0 16,565 33,115 45,005 45,005 59,95 68,382 76,771 88,229 93,711 101,96 110,46 116,46116,46 116,465 116,465 116,465 116,465 116,	0 5,5006 9,4099 13,267 17,437 20,147 20,	0 4192,2 8333,7 12353 16175 19731 23077 26294 29418 32450 32450 32450 32450 32450 32450 32450 32450 32450 32450 35378 40964 43634 44634 46239 448790 51289 51289 51289 55734 56185	0 4,9294 9,6702 11,377 13,534 15,594 17,534 19,547 21,633 23,779 28,155 30,312 32,415 34,464 36,679 38,464 40,462 44,42	0 1597 32,411 44,902 46,108 46,109 46,109 46,109 47,109 71,294 73,215 87,208 94,963 102,51 109,81 113,98 113,98 133,76 144,51 151,2	0 6.2669 11.671 14.545 27.54 36.653 39.812 43.36 47.153 59.602 54.212 54.212 56.133 96.138 96.1086 61.086 64.846 66.698	0 4391,1 8734,3 13007 17136 21064 24773 28352 31855 35303 38702 42058 4555 51904 55118 58297 61435 564525
Force (N) 0 4260.5 8473.5 12560 16445 20063 23479 26776 29988 33114 30147 30147 30147 30147 30147 30147 51725 57823 60276 62688 Case 19 0	15:248 17:397 19:95 22:144 24:355 26:573 28:809 31:0555 31:0555 31:0555 31:0555 31:0555 31:0555 31:0555 310	49,06	25.431 33.048 36.668 39.638 42.552 46.216 50.53 55.41 55.758 60.366 62.365 64.392 66.772 66.772 66.572 67.5755 67.5755 67.5755 67.5755 67.57555 67.57555	0 4337,7 8629,8 12805 12800 20530 20530 20530 24060 27498 30877 34204 37485 40728 43934 43934 43934 43934 43934 43934 43934 43934 43935 54427 55471 65439 68352 Case 20	0 5,6814 11,37 10,369 12,377 14,23 19,209 22,209 22,209 24,81424,814 24,814 24,814 24,81424,814 24,814 24,814 24,81424,814 24,814 24,81424,814 24,814 24,81424,814 24,814 24,81424,814 24,814 24,81424,814 24,81424,814 24,814 24,81424,814 24,81424,814 24,81424,814 24,81424,814 24,81424,814 24,814 24,81424,814 24,814 24,81424,814 24,814 24,81424,814 24,81424,814 24,814 24,81424,81424	0 16,565 33,115 45,005 45,005 59,95 68,382 76,771 88,229 93,711 101,96 110,46 116,46116,46 116,465 116,465 116,465 116,465 116,	0 5,5006 9,4099 13,267 17,437 20,147 20,	0 4192.2 8333,7 12353 16175 26294 26294 26294 29418 32450 35378 38213 40964 43634 46239 51289 53734 48790 51289 53734 56130 58485 66801	0 4,5294 9,6702 11,1377 13,354 15,594 21,559 25,963 25,963 25,963 26,453 30,312 25,963 20,312 32,415 34,464 36,479 38,464 40,462 44,427 44,42 46,259	0 1597 32,411 44,002 40,43 46,108 54,937 71,234 77,208 94,963 102,51 109,81 116,98 133,93 133,93 137,76 144,51 151,2 157,26	0 6.2699 11.671 14.545 18.668 2.2,94 2.3,47 3.1,83 3.9,482 3.9,482 3.9,482 3.9,482 5.6,633 5.0,138 6.0,960 6.6,977 6.8,486 6.6,698	0 4391,11 8734,3 13007 17136 21064 24773 31855 35303 38702 42058 45375 48655 51904 45375 48655 51904 45375 64355 64355 64355 64355 67564 70535 67564 70535
Force (N) 0	15:248 17:297 19:05 22:144 24:355 26:574 28:809 31:005 33:367 34:367 35:366 35:367 35:366 35:367 35:366 35:367 35:366 35:367 35:366 35:367 35:366 35:367 35:366 35:367 35:366 35:367 35:366 35:367 35:366 35:367 35:367 35:367 35:366 35:367 35:	49.06 57.495 65.809 73.822 81.589 96.055 102.85	28.431 33.048 36.668 36.668 42.552 46.216 50.53 50.549 66.672 66.672 66.672 66.513 50.53 50.5488 50.5488 50.5488 50.5488 50.5488 50.5488 50.5488 50.5488	0 4337,77 8629,8 12805 167900 20530 24060 27498 30877 34204 37485 40728 49334 47106 50244 53350 56427 59471 62476 65439 68352 Case 20 (N) Max	0 5,6814 11,37 10,369 12,377 14,23 16,663 19,529 22,391 22,814 22,814 22,814 22,814 22,814 22,814 22,814 22,814 23,868 44,333 47,019 49,658 52,248 54,77	0 16,565 33,115 46,602 42,605 51,076 46,95 46,95 46,95 46,95 46,95 46,95 10,16 47,17	0 5,5005 9,4999 13,267 17,437 20,043 23,476 23,476 33,695 33,695 33,695 33,695 33,695 33,695 33,695 40,052 43,214 45,91 48,614 45,112 53,462 55,795 58,861 60,559 0 0 0 0 0 0 0 0 0 0 0 0 0	0 4192.2 8333.7 12353 16175 26294 26294 26294 29418 32450 35378 38213 40964 45634 46639 51289 53734 48790 51289 53734 56130 58485 560801 Case 21	0 4,5294 9,6702 11,1377 13,354 15,594 21,559 25,963 25,963 25,963 26,453 30,312 25,963 20,312 32,415 34,464 36,479 38,464 40,462 44,427 44,42 46,259	0 1597 32,411 44,702 40,43 46,108 54,237 71,234 77,238 97,208 94,963 102,51 109,81 116,98 123,98 130,93 137,76 144,51 151,2 157,86	0 6.2699 11.671 14.545 18.668 2.2,94 2.3,47 3.1,83 3.9,482 3.9,482 3.9,482 3.9,482 5.6,633 5.0,138 6.0,960 6.6,977 6.8,486 6.6,698	0 4391,11 8734,3 13007 17136 22064 24773 31855 335303 38702 42058 45375 48655 51904 45375 48655 51904 45375 48655 51904 55118 88297 61435 61556 7564 70535 Case 22
Force (N)	115.248 17.397 19.955 22.144 24.355 26.573 26.573 27.840 31.045 3	49.06 57.495 65.809 73.822 81.889 96.085 102.85 102.85 102.85 102.85 121.63 121.63 127.48 133.31 133.59 144.51 22a) ss in Tenon Max Stree	25.431 33.048 36.668 39.638 42.552 46.216 50.53 55.41 55.758 60.366 62.365 64.392 66.772 66.772 66.572 67.5755 67.5755 67.5755 67.5755 67.57555 67.57555	0 0 4337,7 8629,8 12805 16790 24060 24060 24496 30877 34204 37485 40728 4934 47106 54427 54471 62476 65439 68352 Case 20 (N) Max	0 5,6814 11,37 10,369 12,377 14,22,377 14,22,377 14,22,377 14,2577 14,2577 14,2577 14,2577 14	0 16,565 33,115 42,695 42,695 42,695 43,935 64,371 76,371 76,371 76,371 76,371 76,371 76,371 76,371 76,371 10,199 110,16 118,41 126,55 134,66 142,83 150,84 158,71 166,33	0 5,5005 9,4999 13,267 17,437 20,045 23,476 23,476 23,476 33,675 33,675 33,675 33,675 33,675 34,514 45,91 48,514 45,91 48,514 45,91 48,514 55,795 58,561 60,559	0 4192.2 8333.7 12353 16175 19731 23077 26294 23077 26294 32450 35378 38213 38213 38213 38213 38213 40964 43534 42639 435378 4256 5130 5130 5130 5130 56480 56480 56480 Case 21	0 4.5294 9.6702 11.1377 13.534 15.594 17.534 17.534 17.544 13.579 25.663 25.663 25.663 26.679 34.464 34.464 34.464 44.42 46.359 20.012 23.455 24.55 24.55 24.55 24.55 24.55 25.653 24.454 24.454 24.55 25.555 26.559 26.555 2	0 1597 32,411 44,702 40,43 46,108 54,19 66,107 77,728 79,315 87,728 87,728 89,102,51 109,81 116,98 123,98 130,93 137,76 144,51 151,2 157,26	0 6.2699 11.671 14.545 18.668 2.2,94 2.7,347 3.1,83 3.6,433 3.6,433 3.6,433 3.6,433 3.4,343 3.3,435 5.0,602 5.6,633 5.0,138 6.0,907 6.8,346 6.6,698 6.6,597 0 0 0	0 4391,11 8734,3 13007 17136 22064 24773 38352 31855 35303 883702 4058 44535 44655 44525 6744 51904 51904 51904 51904 2425 67564 70335 64225 67564 70335 64225 67564 70335 8207 8207 8207 8207 8207 8207 8207 8207
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Force (N) 0 4391,1 8734,3 13007 17136 21064 24773 28352 31855 35303 38702 42058 45375 48655 51904 55118 58297 61435	15 248 17,797 19,95 22,144 24,355 26,573 28,809 31,055	40.06 57,909 65,800 73,822 81,389 84,404 90,823 11,363 102,33 112,16 127,48 133,31 133,31 134,465 00 15,827 32,208 49,178 48,818 49,778 48,818 49,780 48,818 49,781 49,782 49,466 102,22 109,96 117,49 124,87 132,21	28.431 33.048 34.608 34.608 34.608 42.552 442.552 442.552 442.552 442.552 442.552 45.758 45.875 45.875 45.875 45.875 45.875 45.875 45.875 45.875 45.875 45.885 45.875 45.885 4	0 4337.7 8629.8 4337.7 8629.8 4337.7 8629.8 4337.4 2430.6 2440.0 244	0 5.6814 11.37 10.509 12.377 10.539 10.539 10.201 22.009 24.814 22.643 30.471 33.208 36.092 38.863 44.1534 11.188	0 16,565 33,115 39,514 46,603 59,955 68,382 76,771 10,99 110,16 113,46 124,66 144,66 144,66 144,66 144,66 150,844 150,871 166,33 166,33 166,33 166,438 20,75 45,429 100,10 14,658 20,75 45,429 160,20 14,658 20,75 45,429 160,20 14,658 20,75 45,429 160,20 160,2	0 5,506 9,4999 13,267 17,473 52,476 23,476 20,26869 20,0186 33,473 35,86 33,473 35,86 33,473 44,531 44,531 44,531 44,531 44,531 60,059 60,059 60,059 60,059 60,059 60,059 11,205	0 4192,2 8333,7 16175 22531 20294 20	0 4,5294 9,6702 11,137 15,594 15,594 15,594 15,594 15,594 15,594 25,565 28,155 28,155 28,155 28,155 28,155 28,243 24,153 24,153 24,153 24,154 24,457 25,459 27,453 29,564 31,614 33,569 35,664 35,664 35,664 35,664 35,665 35,	0 15.97 32.41 44.90 46.33 44.61 44.90 46.33 46.41 45.90 46.34 46.41 62.787 71.294 73.915 87.208 94.963 102.51 109.81 116.98 116.98 130.93 130.93 130.93 130.93 130.93 130.93 130.93 130.93 130.93 130.93 130.93 130.93 130.93 144.51 157.86 144.51 157.86 10 144.666 22.9717 152.21 157.86 144.51 157.86 144.54 152.507 161.724 170.531 179.187 87.839 96.497 105 113.66 122.466 131.24 13.64 131.24 13.943 13.84 13.943 13.84 13.94 13.84 13.94 13.84 13.94 13.84 13.94 13.84 13.94 13.84 13.94 13.84 13.94 13.84 13.94	0 6.2699 11.671 14.545 13.668 2.9.97 2.9.777 2.9.777 2.9.777 2.9.7777 2.9.7777777777	0 439(1) 439(1) 13007 17136 23052 3383702 42058 45375 48655 31904 3317 64435 64525 67554 64525 67554 70535 Case 22 55 55 55 55 55 55 55 55 55 55 55 55 5
Force (N) 0 4391,11 8734,3 13007 17136 21064 24773 28352 31855 35303 38702 42058 42058 45375 48655 51904 55118 58297 614325	15 244 17,797 19,95 22,144 24,555 25,574 23,5574 23,5574 23,5574 23,5574 23,5574 23,5574 23,5574 23,5574 23,5574 23,5574 23,5574 24,557 24,557 27,556 27,556 27,556 27,556 27,557 27,577 27,5	40.06 57.493 65.800 73.822 81.580 96.085 96.085 96.085 96.085 97.3822 96.085 96.085 97.382 121.4 127.48 127.48 127.48 127.48 127.48 133.31 138.98 144.51 98.144.51 98.144.51 98.144.51 98.145 98.145 98.145 99.178 49.792 49.7165 55.106 55.10	28.431 33.948 34.608 36.608 36.608 42.552 42.552 42.516 30.513 42.526 50.513 50.516 50.722 66.672 66.672 66.672 66.723 66.722 66.513 10.076 52.858 10.285 10.076 52.858 10.075 52.858 10.075 52.858 10.075 52.858 10.075 52.858 10.075 52.858 10.075	0 0 0 0 0 0 0 0 4337.7 8629.8 4337.7 8629.8 4337.4 1280 10500 27498 2400 27498 2400 27498 3420 2400 27498 3420 2400 2749 3420 4073 3 4073 4073 4073 4073 4073 4073 4	0 5.6814 11.37 10.507 12.209 24.814 22.643 30.471 30.209 24.814 22.643 30.471 30.209 24.814 30.471 30.209 24.814 30.471 30.209 24.814 40.638 41.615 44.334 47.019 49.658 54.728 54.728 54.728 54.728 54.728 54.728 54.728 54.728 54.728 54.728 54.728 54.728 55.518 52.518 5	0 16,565 33,115 39,514 44,605 59,95 68,382 76,771 88,229 93,711 10,10 94,711 10,56 113,44 125,56 142,83 159,84 159,85	0 5,506 9,409 13,267 13,267 23,476 23,2476 23,2476 23,2476 23,2476 23,2476 23,2476 23,2476 23,2476 23,247 24,251 24,253,462 24,514 25,354 24,514 25,354 24,514 25,354 20 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	0 4192.2 8333.7 12355 12355 12357 12357 12357 26294 133240 209418 32450 338213 32450 46339 46539 46539 46539 46534 46539 46539 46545 46539 46545 46539 46545 46545 46545 46545 46545 46545 46545 46545 46545 46545 46545 46545 46545 465545 31570 339275 24582 246	0 4,5294 9,6702 11,1337 11,337 11,337 11,337 11,538 11,538 12,538 22,538 23,135 24	0 15.97 32,411 32,411 44,013 44,013 44,013 62,787 71,294 79,315 87,708 94,905 10,91 10,98	0 6.2699 11.671 14.548 2724 2724 2734 2734 2734 2734 2734 2734	0 439(1) 13007 21064 429(7) 31805 42973 31855 35503 42058 42058 42058 42058 42058 42058 42058 42058 42058 440551 64325 67564 70335 6756 282 285 55 55 55 55 55 55 55 55 55 55 55 55 5
Force (N) 0 4391,11 8734,3 13007 17136 21064 24773 28352 31855 35303 38702 42058 45375 48655 51904 55118 58297 614355 64525 67564	15 248 17,797 19,955 22,144 24,355 26,573 28,809 31,045 31,045 31,045 31,045 31,045 31,045 31,045 31,045 31,045 41,144 41,398 44,357 47,295 47,275	40.06 57,903 65,800 73,822 81,380 84,440 90,823 81,380 102,83 102,83 102,83 115,63 127,48 133,93 146,51 146,51 15,827 32,208 49,178 48,818 49,778 48,818 49,755,1006 63,044 70,621 78,31 98,466 102,32 109,96 117,49 124,87 132,21 139,28 146,22	28.431 33.948 34.608 34.608 34.608 42.552 42.552 42.552 42.552 42.552 42.553 42.855 42.865	0 0 0 0 0 0 0 0 0 0 0 0 0 0	0 5.6814 11.37 10.509 12.377 10.539 10.539 10.201 22.009 24.814 22.643 30.471 33.208 36.092 38.863 44.1513 44.019 44.019 44.053 54.778 55.777 55.	0 16,565 33,115 39,514 46,603 59,955 68,382 76,771 10,99 110,16 113,46 124,66 144,66 144,66 144,66 144,66 150,844 150,871 166,33 166,33 166,33 166,33 166,45 164,478 166,458 162,75 163,90 14,658 129,75 164,658 129,75 164,658 129,75 165,645 164,478 165,645 164,478 165,645 164,478 165,645 164,478 165,855	0 5,506 9,4999 13,267 13,267 17,473 42,374 23,246 20,5689 20,0,86 33,473 35,36 37,259 40,452 44,519 44,519 44,519 45,112 55,295 55,295 55,205	0 4192,2 8333,7 16175 23377 26394 23397 26394 23397 26394 20397 20	0 4,5294 9,6702 11,137 15,594 17,534 19,547 25,563 28,155 28,	0 15.97 32.41 44.90 46.33 44.61 44.90 46.33 46.41 45.90 46.34 46.41 62.787 71.294 73.915 87.208 94.963 102.51 109.81 116.98 116.98 130.93 130.93 130.93 130.93 130.93 130.93 130.93 130.93 130.93 130.93 130.93 130.93 130.93 144.51 157.86 144.51 157.86 10 144.666 22.9717 152.21 157.86 144.51 157.86 144.54 152.507 161.724 170.531 179.187 87.839 96.497 105 113.66 122.466 131.24 13.64 131.24 13.943 13.84 13.943 13.84 13.94 13.84 13.94 13.84 13.94 13.84 13.94 13.84 13.94 13.84 13.94 13.84 13.94 13.84 13.94	0 6.2699 11.671 14.545 15.668 2.947 2.947 2.947 2.947 3.6633 3.9412 3.9412 3.9412 4.356 4.133 5.9602 5.953 3.9412 5.953 3.9412 5.953 3.9412 5.953 3.9412 5.953 3.9412 5.953 3.9412 5.953 3.9412 5.953 3.9412 5.953 4.135 6.64346 6.6597 6.64346 6.6597 6.64346 6.6597 6.64346 6.6598 8.000 5.881 1.000 5.881 1.000 5.881 1.000 5.881 1.000 5.881 1.000 5.881 1.000 5.881 1.000 5.881 1.000 1.000 5.881 1.000 5.885 1.000 5.885 1.000 5.885 1.000 5.885 1.000 5.885 1.000 5.885 1.000 5.885 1.000 5.885 1.000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.00000 5.885 1.00000 5.885 1.00000 5.885 1.00000 5.885 1.000000 5.885 1.000000000000000000000000000000000000	0 0 4391,1 3607 13007 17136 21073 2552 33502 33502 38702 42058 45375 48655 51904 51904 51904 51904 64355 67564 67564 70335 Case 22 55 55 55 56 33 56 44 67 64 55 144 67 143 33 144 67 144 67 143 33 144 67 144 67 144 67 144 67 144 67 144 67 144 68 144 68 144
Force (N) 0 4391,11 8734,3 13007 17136 21064 24773 28352 31855 35303 38702 42058 42058 42058 45557 51904 455118 58297 614355 64525	15 244 17,797 19,95 22,144 24,555 25,574 23,5574 23,5574 23,5574 23,5574 23,5574 23,5574 23,5574 23,5574 23,5574 23,5574 23,5574 24,557 24,557 27,556 27,556 27,556 27,556 27,557 27,577 27,5	40.06 57.493 65.800 73.822 81.580 96.085 96.085 96.085 96.085 97.3822 96.085 96.085 97.382 121.4 127.48 127.48 127.48 127.48 127.48 133.31 138.98 144.51 98.144.51 98.144.51 98.144.51 98.145 98.145 98.145 99.178 49.792 49.7165 55.106 55.10	28.431 33.948 34.608 36.608 36.608 42.552 42.552 42.516 30.513 42.526 50.513 50.516 50.722 66.672 66.672 66.672 66.723 66.722 66.513 10.076 52.858 10.285 10.076 52.858 10.075 52.858 10.075 52.858 10.075 52.858 10.075 52.858 10.075 52.858 10.075	0 0 0 0 0 0 0 0 0 0 0 0 0 0	0 5.6814 11.37 10.507 12.209 24.814 22.643 30.471 30.209 24.814 22.643 30.471 30.209 24.814 30.471 30.209 24.814 30.471 30.209 24.814 40.638 41.615 44.634 47.019 49.638 44.615 44.634 47.019 49.638 54.778 54.778 54.778 54.778 54.778 54.778 54.778 52.248 54.778 52.248 54.778 52.248 54.778 52.25.18 52.261 52.518 52.25.18 52.25.18 52.25.18 52.25.18 52.25.18 52.25.18 52.25.18 52.25.18 52.25.18 53.799 53.828 53.827 53.827 53.827 53.827 53.828 53.82 53.	0 16,565 33,115 39,514 44,605 59,95 68,382 76,771 88,229 93,711 10,10 94,711 10,56 113,44 125,56 142,83 159,84 159,85	0 5,506 9,409 13,267 13,267 23,476 23,2476 23,2476 23,2476 23,2476 23,2476 23,2476 23,2476 23,2476 23,247 24,251 24,253,462 24,514 25,354 24,514 25,354 24,514 25,354 20 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	0 4192.2 8333.7 12355 12355 12357 12357 12357 26294 133240 209418 32450 338213 32450 46339 46539 46539 46539 46534 46539 46539 46545 46539 46545 46539 46545 46545 46545 46545 46545 46545 46545 46545 46545 46545 46545 46545 46545 465545 31570 339275 24582 246	0 4,5294 9,6702 11,1337 11,337 11,337 11,337 11,538 11,538 12,538 22,538 23,135 24	0 15.97 32,411 32,411 44,013 44,013 44,013 62,787 71,294 79,315 87,708 94,905 10,91 10,98	0 6.2699 11.671 14.548 2724 2724 2734 2734 2734 2734 2734 2734	0 0 4391,1 3607 13007 17136 21073 2552 33502 33502 38702 42058 45375 48655 51904 51904 51904 51904 64355 67564 67564 70335 Case 22 55 55 55 56 33 56 44 67 64 55 144 67 143 33 144 67 144 67 143 33 144 67 144 67 144 67 144 67 144 67 144 67 144 68 144 68 144
Force (N) 0 4391,11 8734,3 13007 17136 21064 24773 28352 31855 35303 38702 42055 35303 38702 42055 51904 55118 58297 61435 64525 67564	15 248 17,797 19,955 22,144 24,355 26,573 28,809 31,045 31,045 31,045 31,045 31,045 31,045 31,045 31,045 31,045 41,144 41,398 44,357 47,295 47,275	40.06 57,903 65,800 73,822 81,380 84,440 90,823 81,380 102,83 102,83 102,83 115,63 127,48 133,93 146,51 146,51 15,827 32,208 49,178 48,818 49,778 48,818 49,755,1006 63,044 70,621 78,31 98,466 102,32 109,96 117,49 124,87 132,21 139,28 146,22	28.431 33.948 34.608 34.608 34.608 42.552 42.552 42.552 42.552 42.552 42.553 42.855 42.865	0 0 4337.7 8629.8 4337.7 8629.8 10700 10700 22400 2400 22400 2400 22400 2400 23400 2400 2400 2400 2400 2400 2400 2400 2400 2400 2400 30877 34204 47106 47106 54071 6332 54071 64352 54071 64352 64352 2.3 54071 64352 64352 2.3 54071 64352 64352 2.3 54071 64352 64352 2.3 5417 3.3 5417 3.3 5417 3.4 5416 3.5 5 5 5 5 5 5 5 5	0 5.6814 11.37 10.509 12.377 10.539 10.539 10.201 22.009 24.814 22.643 30.471 33.208 36.092 38.863 44.1513 44.019 44.019 44.053 54.778 55.777 55.	0 16,565 33,115 39,514 46,603 59,955 68,382 76,771 10,99 110,16 113,46 124,66 144,66 144,66 144,66 144,66 150,844 150,871 166,33 166,33 166,33 166,33 166,45 164,478 166,458 162,75 163,90 14,658 129,75 164,658 129,75 164,658 129,75 165,645 164,478 165,645 164,478 165,645 164,478 165,645 164,478 165,855	0 5,506 9,4999 13,267 13,267 17,473 42,374 23,246 20,5689 20,0,86 33,473 35,36 37,259 40,452 44,519 44,519 44,519 45,112 55,295 55,295 55,205	0 4192,2 8333,7 16175 23377 26394 23397 26394 23397 26394 20397 20	0 4,5294 9,6702 11,137 15,594 17,534 19,547 25,563 28,155 28,	0 15.97 32,411 32,411 44,013 44,013 44,013 62,787 71,294 79,315 87,708 94,905 10,91 10,98	0 6.2699 11.671 14.545 15.668 2.947 2.947 2.947 2.947 3.6633 3.9412 3.9412 3.9412 4.356 4.133 5.9602 5.953 3.9412 5.953 3.9412 5.953 3.9412 5.953 3.9412 5.953 3.9412 5.953 3.9412 5.953 3.9412 5.953 3.9412 5.953 4.135 6.64346 6.6597 6.64346 6.6597 6.64346 6.6597 6.64346 6.6598 8.000 5.881 1.000 5.881 1.000 5.881 1.000 5.881 1.000 5.881 1.000 5.881 1.000 5.881 1.000 5.881 1.000 1.000 5.881 1.000 5.885 1.000 5.885 1.000 5.885 1.000 5.885 1.000 5.885 1.000 5.885 1.000 5.885 1.000 5.885 1.000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.0000 5.885 1.00000 5.885 1.00000 5.885 1.00000 5.885 1.00000 5.885 1.000000 5.885 1.000000000000000000000000000000000000	0 4991,41 4391,41 4391,41 4391,41 4391,41 4391,41 4391,41 4391,41 4391,41 4391,41 4203,41 420,41 4203,

Load Calculator Inputs in Green village, Delft

Load combination

g .k	Permanent load
q .k	Live load
S .k	Snow load
W.k	Wind load

Permanent load

	Per area	Applied on one element
Roof	1.1 kN/m ²	-
Walls	4.5 kN/m^2	4.4 kN/m
Beams	later	1.38 kN/m
Columns	later	2.76 kN
Floor	0.9 kN/m^2	-

Snow load

	Applied on one elements
Sk	0.56 kN/m^2
Beams	1.7 kN/m
Columns	1.4 kN

	Douglas fir	European spruce	European Larch
y.m	1.3	1.3	1.3
ρ (Kg/m3)⁴	550	440	610
fm.k (N/mm3)	86	63	91
fv.k (N/mm3)	8.2	5.3	9
fc.k (N/mm3)	42	35	45
E (kN/mm3)	12.17	9.7	11.2
k. mod.p	0.5	0.5	0.5
k. mod.m	0.65	0.65	0.65
k. mod.i	0.90	0.90	0.90
k. def	2	2	2
P.∟ (kN/m)	2.96	2.96	2.96
M.∟(kN/m)	7.44	7.44	7.44
l.∟(kN/m)	5.66	5.66	5.66
SLS.∟(kN/m)	5.18	5.18	5.18
g k (kN/m)	1.38	1.38	1.38
g.lead (kN/m)	2	2	2
g.acm (kN/m)	1.4	1.4	1.4
psi.lead	0	0	0
psi.acmp	0.2	0.2	0.2
B.c	0.2	0.2	0.2

Material properties, Values, Variables used in the optimisation of timber frames

⁴ Air-dried (around 12-15% moisture content)

P.clm	3.1	3.4	2.9
M.clm	7.1	8.6	8.3
I.clm	6.1	7.2	7

Optimisation results for timber frame Douglas Fir

Weight (kg)	Width (mm)	Thickne ss (mm)	Bending Util (%)	Bending Status	Shear Util (%)	Shear Status	SLS Util (%)	SLS Status	Compre ssion Util (%)	Compre ssion Status	Bucklin g Util Y (%)	Bucklin g Status Y	Bucklin g Util Z (%)	Bucklin g Status Z	Final Util (%)	Final Status
10.45	95	100	54.64%	Accepta ble	28.65%	Accepta ble	168.01 %	Unacce ptable	5.02%	Accepta ble	7.97%	Accepta ble	8.66%	Accepta ble	168.01 %	Unacce ptable
11.00	100	100	51.91%	Accepta ble	27.22%	Accepta ble	159.61 %	Unacce ptable	4.77%	Accepta ble	7.57%	Accepta ble	7.57%	Accepta ble	159.61 %	Unacce ptable
11.50	95	110	45.16%	Accepta ble	26.05%	Accepta ble	126.23 %	Unacce ptable	4.56%	Accepta ble	6.27%	Accepta ble	7.87%	Accepta ble	126.23 %	Unacce ptable
12.02	95	115	41.31%	Accepta ble	24.91%	Accepta ble	110.47 %	Unacce ptable	4.36%	Accepta ble	5.63%	Accepta ble	7.53%	Accepta ble	110.47 %	Unacce ptable
12.10	100	110	42.90%	Accepta ble	24.75%	Accepta ble	119.92 %	Unacce ptable	4.33%	Accepta ble	5.95%	Accepta ble	6.88%	Accepta ble	119.92 %	Unacce ptable
12.54	95	120	37.94%	Accepta ble	23.88%	Accepta ble	97.23%	Accepta ble	4.18%	Accepta ble	5.10%	Accepta ble	7.22%	Accepta ble	97.23%	Accepta ble
12.65	100	115	39.25%	Accepta ble	23.67%	Accepta ble	104.95 %	Unacce ptable	4.14%	Accepta ble	5.35%	Accepta ble	6.58%	Accepta ble	104.95 %	Unacce ptable
12.65	115	100	45.14%	Accepta ble	23.67%	Accepta ble	138.79 %	Unacce ptable	4.14%	Accepta ble	6.58%	Accepta ble	5.35%	Accepta ble	138.79 %	Unacce ptable
13.06	95	125	34.97%	Accepta ble	22.92%	Accepta ble	86.02%	Accepta ble	4.01%	Accepta ble	4.66%	Accepta ble	6.93%	Accepta ble	86.02%	Accepta ble
13.20	100	120	36.05%	Accepta ble	22.68%	Accepta ble	92.37%	Accepta ble	3.97%	Accepta ble	4.85%	Accepta ble	6.31%	Accepta ble	92.37%	Accepta ble
13.58	95	130	32.33%	Accepta ble	22.04%	Accepta ble	76.47%	Accepta ble	3.86%	Accepta ble	4.29%	Accepta ble	6.66%	Accepta ble	76.47%	Accepta ble
13.75	100	125	33.22%	Accepta ble	21.78%	Accepta ble	81.72%	Accepta ble	3.81%	Accepta ble	4.43%	Accepta ble	6.06%	Accepta ble	81.72%	Accepta ble
13.75	125	100	41.53%	Accepta ble	21.78%	Accepta ble	127.69 %	Unacce ptable	3.81%	Accepta ble	6.06%	Accepta ble	4.43%	Accepta ble	127.69 %	Unacce ptable
13.91	115	110	37.30%	Accepta ble	21.52%	Accepta ble	104.28 %	Unacce ptable	3.77%	Accepta ble	5.18%	Accepta ble	4.86%	Accepta ble	104.28 %	Unacce ptable

14.11	95	135	29.98%	Accepta	21.22%	Accepta	68.29%	Accepta	3.72%	Accepta	3.98%	Accepta	6.41%	Accepta	68.29%	Accepta
				ble		ble		ble		ble		ble		ble		ble
14.30	100	130	30.71%	Accepta ble	20.94%	Accepta ble	72.65%	Accepta ble	3.67%	Accepta ble	4.08%	Accepta ble	5.82%	Accepta ble	72.65%	Accepta ble
14.55	115	115	34.13%	Accepta ble	20.58%	Accepta ble	91.26%	Accepta ble	3.60%	Accepta ble	4.65%	Accepta ble	4.65%	Accepta ble	91.26%	Accepta ble
14.63	95	140	27.88%	Accepta ble	20.47%	Accepta ble	61.23%	Accepta ble	3.58%	Accepta ble	3.71%	Accepta ble	6.19%	Accepta ble	61.23%	Accepta ble
14.85	100	135	28.48%	Accepta ble	20.16%	Accepta ble	64.87%	Accepta ble	3.53%	Accepta ble	3.78%	Accepta ble	5.61%	Accepta ble	64.87%	Accepta ble
15.12	125	110	34.32%	Accepta ble	19.80%	Accepta ble	95.94%	Accepta ble	3.47%	Accepta ble	4.76%	Accepta ble	4.03%	Accepta ble	95.94%	Accepta ble
15.15	95	145	25.99%	Accepta ble	19.76%	Accepta ble	55.11%	Accepta ble	3.46%	Accepta ble	3.48%	Accepta ble	5.97%	Accepta ble	55.11%	Accepta ble
15.18	115	120	31.34%	Accepta ble	19.72%	Accepta ble	80.32%	Accepta ble	3.45%	Accepta ble	4.22%	Accepta ble	4.46%	Accepta ble	80.32%	Accepta ble
15.18	138	100	37.61%	Accepta ble	19.72%	Accepta ble	115.66 %	Unacce ptable	3.45%	Accepta ble	5.49%	Accepta ble	3.62%	Accepta ble	115.66 %	Unacce ptable
15.40	100	140	26.48%	Accepta ble	19.44%	Accepta ble	58.17%	Accepta ble	3.40%	Accepta ble	3.52%	Accepta ble	5.41%	Accepta ble	58.17%	Accepta ble
15.67	95	150	24.28%	Accepta ble	19.10%	Accepta ble	49.78%	Accepta ble	3.35%	Accepta ble	3.27%	Accepta ble	5.77%	Accepta ble	49.78%	Accepta ble
15.81	115	125	28.89%	Accepta ble	18.94%	Accepta ble	71.06%	Accepta ble	3.32%	Accepta ble	3.85%	Accepta ble	4.28%	Accepta ble	71.06%	Accepta ble
15.81	125	115	31.40%	Accepta ble	18.94%	Accepta ble	83.96%	Accepta ble	3.32%	Accepta ble	4.28%	Accepta ble	3.85%	Accepta ble	83.96%	Accepta ble
15.95	100	145	24.69%	Accepta ble	18.77%	Accepta ble	52.36%	Accepta ble	3.29%	Accepta ble	3.30%	Accepta ble	5.22%	Accepta ble	52.36%	Accepta ble
16.20	95	155	22.74%	Accepta ble	18.49%	Accepta ble	45.12%	Accepta ble	3.24%	Accepta ble	3.10%	Accepta ble	5.59%	Accepta ble	45.12%	Accepta ble
16.45	115	130	26.71%	Accepta ble	18.21%	Accepta ble	63.17%	Accepta ble	3.19%	Accepta ble	3.54%	Accepta ble	4.12%	Accepta ble	63.17%	Accepta ble
16.50	100	150	23.07%	Accepta ble	18.15%	Accepta ble	47.29%	Accepta ble	3.18%	Accepta ble	3.11%	Accepta ble	5.05%	Accepta ble	47.29%	Accepta ble
16.50	125	120	28.84%	Accepta ble	18.15%	Accepta ble	73.90%	Accepta ble	3.18%	Accepta ble	3.88%	Accepta ble	3.69%	Accepta ble	73.90%	Accepta ble
16.50	150	100	34.60%	Accepta ble	18.15%	Accepta ble	106.41 %	Unacce ptable	3.18%	Accepta ble	5.05%	Accepta ble	3.11%	Accepta ble	106.41 %	Unacce ptable
16.70	138	110	31.09%	Accepta ble	17.93%	Accepta ble	86.90%	Accepta ble	3.14%	Accepta ble	4.31%	Accepta ble	3.29%	Accepta ble	86.90%	Accepta ble
16.72	95	160	21.34%	Accepta ble	17.91%	Accepta ble	41.02%	Accepta ble	3.14%	Accepta ble	2.94%	Accepta ble	5.41%	Accepta ble	41.02%	Accepta ble
17.05	100	155	21.61%	Accepta ble	17.56%	Accepta ble	42.86%	Accepta ble	3.08%	Accepta ble	2.94%	Accepta ble	4.88%	Accepta ble	42.86%	Accepta ble

17.00	115	105	0.4.77%		17 500		FC 410		0.07%		0.00%		0.00%		FC 410	
17.08	115	135	24.77%	Accepta ble	17.53%	Accepta ble	56.41%	Accepta ble	3.07%	Accepta ble	3.28%	Accepta ble	3.96%	Accepta ble	56.41%	Accepta ble
17.19	125	125	26.58%	Accepta ble	17.42%	Accepta ble	65.38%	Accepta ble	3.05%	Accepta ble	3.54%	Accepta ble	3.54%	Accepta ble	65.38%	Accepta ble
17.24	95	165	20.07%	Accepta ble	17.36%	Accepta ble	37.40%	Accepta ble	3.04%	Accepta ble	2.81%	Accepta ble	5.25%	Accepta ble	37.40%	Accepta ble
17.46	138	115	28.44%	Accepta ble	17.15%	Accepta ble	76.05%	Accepta ble	3.00%	Accepta ble	3.88%	Accepta ble	3.15%	Accepta ble	76.05%	Accepta ble
17.60	100	160	20.28%	Accepta ble	17.01%	Accepta ble	38.97%	Accepta ble	2.98%	Accepta ble	2.80%	Accepta ble	4.73%	Accepta ble	38.97%	Accepta ble
17.71	115	140	23.03%	Accepta ble	16.91%	Accepta ble	50.58%	Accepta ble	2.96%	Accepta ble	3.06%	Accepta ble	3.82%	Accepta ble	50.58%	Accepta ble
17.88	125	130	24.57%	Accepta ble	16.75%	Accepta ble	58.12%	Accepta ble	2.93%	Accepta ble	3.26%	Accepta ble	3.41%	Accepta ble	58.12%	Accepta ble
18.15	100	165	19.07%	Accepta ble	16.50%	Accepta ble	35.53%	Accepta ble	2.89%	Accepta ble	2.67%	Accepta ble	4.59%	Accepta ble	35.53%	Accepta ble
18.15	150	110	28.60%	Accepta ble	16.50%	Accepta ble	79.95%	Accepta ble	2.89%	Accepta ble	3.97%	Accepta ble	2.83%	Accepta ble	79.95%	Accepta ble
18.22	138	120	26.12%	Accepta ble	16.44%	Accepta ble	66.93%	Accepta ble	2.88%	Accepta ble	3.51%	Accepta ble	3.02%	Accepta ble	66.93%	Accepta ble
18.34	115	145	21.47%	Accepta ble	16.32%	Accepta ble	45.53%	Accepta ble	2.86%	Accepta ble	2.87%	Accepta ble	3.69%	Accepta ble	45.53%	Accepta ble
18.56	125	135	22.78%	Accepta ble	16.13%	Accepta ble	51.90%	Accepta ble	2.82%	Accepta ble	3.02%	Accepta ble	3.28%	Accepta ble	51.90%	Accepta ble
18.98	115	150	20.06%	Accepta ble	15.78%	Accepta ble	41.12%	Accepta ble	2.76%	Accepta ble	2.70%	Accepta ble	3.57%	Accepta ble	41.12%	Accepta ble
18.98	138	125	24.07%	Accepta ble	15.78%	Accepta ble	59.22%	Accepta ble	2.76%	Accepta ble	3.21%	Accepta ble	2.90%	Accepta ble	59.22%	Accepta ble
18.98	150	115	26.17%	Accepta ble	15.78%	Accepta ble	69.97%	Accepta ble	2.76%	Accepta ble	3.57%	Accepta ble	2.70%	Accepta ble	69.97%	Accepta ble
19.25	175	100	29.66%	Accepta ble	15.55%	Accepta ble	91.21%	Accepta ble	2.72%	Accepta ble	4.33%	Accepta ble	2.44%	Accepta ble	91.21%	Accepta ble
19.25	125	140	21.19%	Accepta ble	15.55%	Accepta ble	46.53%	Accepta ble	2.72%	Accepta ble	2.82%	Accepta ble	3.16%	Accepta ble	46.53%	Accepta ble
19.61	115	155	18.79%	Accepta ble	15.27%	Accepta ble	37.27%	Accepta ble	2.67%	Accepta ble	2.56%	Accepta ble	3.45%	Accepta ble	37.27%	Accepta ble
19.73	138	130	22.26%	Accepta ble	15.17%	Accepta ble	52.65%	Accepta ble	2.66%	Accepta ble	2.95%	Accepta ble	2.78%	Accepta ble	52.65%	Accepta ble
19.80	150	120	24.03%	Accepta ble	15.12%	Accepta ble	61.58%	Accepta ble	2.65%	Accepta ble	3.23%	Accepta ble	2.59%	Accepta ble	61.58%	Accepta ble
19.94	125	145	19.75%	Accepta ble	15.02%	Accepta ble	41.88%	Accepta ble	2.63%	Accepta ble	2.64%	Accepta ble	3.06%	Accepta ble	41.88%	Accepta ble
20.24	115	160	17.63%	Accepta ble	14.79%	Accepta ble	33.89%	Accepta ble	2.59%	Accepta ble	2.43%	Accepta ble	3.34%	Accepta ble	33.89%	Accepta ble

20.49	138	135	20.64%	Accepta	14.61%	Accepta	47.01%	Accepta	2.56%	Accepta	2.74%	Accepta	2.68%	Accepta	47.01%	Accepta
20.15	100		20.01%	ble	1 1.01%	ble	17.01%	ble	2.00%	ble	2.7 170	ble	2.00%	ble	17.01%	ble
20.62	125	150	18.46%	Accepta ble	14.52%	Accepta ble	37.83%	Accepta ble	2.54%	Accepta ble	2.49%	Accepta ble	2.95%	Accepta ble	37.83%	Accepta ble
20.62	150	125	22.15%	Accepta ble	14.52%	Accepta ble	54.48%	Accepta ble	2.54%	Accepta ble	2.95%	Accepta ble	2.49%	Accepta ble	54.48%	Accepta ble
20.87	115	165	16.58%	Accepta ble	14.34%	Accepta ble	30.90%	Accepta ble	2.51%	Accepta ble	2.32%	Accepta ble	3.24%	Accepta ble	30.90%	Accepta ble
21.18	175	110	24.51%	Accepta ble	14.14%	Accepta ble	68.53%	Accepta ble	2.48%	Accepta ble	3.40%	Accepta ble	2.22%	Accepta ble	68.53%	Accepta ble
21.25	138	140	19.19%	Accepta ble	14.09%	Accepta ble	42.15%	Accepta ble	2.47%	Accepta ble	2.55%	Accepta ble	2.58%	Accepta ble	42.15%	Accepta ble
21.31	125	155	17.28%	Accepta ble	14.05%	Accepta ble	34.29%	Accepta ble	2.46%	Accepta ble	2.35%	Accepta ble	2.86%	Accepta ble	34.29%	Accepta ble
21.45	150	130	20.48%	Accepta ble	13.96%	Accepta ble	48.43%	Accepta ble	2.44%	Accepta ble	2.72%	Accepta ble	2.39%	Accepta ble	48.43%	Accepta ble
22.00	125	160	16.22%	Accepta ble	13.61%	Accepta ble	31.17%	Accepta ble	2.38%	Accepta ble	2.24%	Accepta ble	2.77%	Accepta ble	31.17%	Accepta ble
22.01	138	145	17.89%	Accepta ble	13.60%	Accepta ble	37.94%	Accepta ble	2.38%	Accepta ble	2.39%	Accepta ble	2.50%	Accepta ble	37.94%	Accepta ble
22.14	175	115	22.43%	Accepta ble	13.53%	Accepta ble	59.97%	Accepta ble	2.37%	Accepta ble	3.06%	Accepta ble	2.12%	Accepta ble	59.97%	Accepta ble
22.28	150	135	18.99%	Accepta ble	13.44%	Accepta ble	43.25%	Accepta ble	2.35%	Accepta ble	2.52%	Accepta ble	2.30%	Accepta ble	43.25%	Accepta ble
22.69	125	165	15.25%	Accepta ble	13.20%	Accepta ble	28.43%	Accepta ble	2.31%	Accepta ble	2.13%	Accepta ble	2.68%	Accepta ble	28.43%	Accepta ble
22.77	138	150	16.72%	Accepta ble	13.15%	Accepta ble	34.27%	Accepta ble	2.30%	Accepta ble	2.25%	Accepta ble	2.41%	Accepta ble	34.27%	Accepta ble
23.10	175	120	20.60%	Accepta ble	12.96%	Accepta ble	52.78%	Accepta ble	2.27%	Accepta ble	2.77%	Accepta ble	2.04%	Accepta ble	52.78%	Accepta ble
23.10	150	140	17.66%	Accepta ble	12.96%	Accepta ble	38.78%	Accepta ble	2.27%	Accepta ble	2.35%	Accepta ble	2.22%	Accepta ble	38.78%	Accepta ble
23.53	138	155	15.66%	Accepta ble	12.73%	Accepta ble	31.06%	Accepta ble	2.23%	Accepta ble	2.13%	Accepta ble	2.33%	Accepta ble	31.06%	Accepta ble
23.92	150	145	16.46%	Accepta ble	12.51%	Accepta ble	34.90%	Accepta ble	2.19%	Accepta ble	2.20%	Accepta ble	2.15%	Accepta ble	34.90%	Accepta ble
24.06	175	125	18.98%	Accepta ble	12.44%	Accepta ble	46.70%	Accepta ble	2.18%	Accepta ble	2.53%	Accepta ble	1.95%	Accepta ble	46.70%	Accepta ble
24.29	138	160	14.69%	Accepta ble	12.33%	Accepta ble	28.24%	Accepta ble	2.16%	Accepta ble	2.03%	Accepta ble	2.26%	Accepta ble	28.24%	Accepta ble
24.75	150	150	15.38%	Accepta ble	12.10%	Accepta ble	31.53%	Accepta ble	2.12%	Accepta ble	2.07%	Accepta ble	2.07%	Accepta ble	31.53%	Accepta ble
25.02	175	130	17.55%	Accepta ble	11.96%	Accepta ble	41.51%	Accepta ble	2.10%	Accepta ble	2.33%	Accepta ble	1.88%	Accepta ble	41.51%	Accepta ble

25.05	138	165	13.82%	Accepta ble	11.95%	Accepta ble	25.75%	Accepta ble	2.09%	Accepta ble	1.93%	Accepta ble	2.19%	Accepta ble	25.75%	Accepta ble
25.57	150	155	14.40%	Accepta ble	11.71%	Accepta ble	28.57%	Accepta ble	2.05%	Accepta ble	1.96%	Accepta ble	2.01%	Accepta ble	28.57%	Accepta ble
25.99	175	135	16.27%	Accepta ble	11.52%	Accepta ble	37.07%	Accepta ble	2.02%	Accepta ble	2.16%	Accepta ble	1.81%	Accepta ble	37.07%	Accepta ble
26.40	150	160	13.52%	Accepta ble	11.34%	Accepta ble	25.98%	Accepta ble	1.99%	Accepta ble	1.86%	Accepta ble	1.94%	Accepta ble	25.98%	Accepta ble
26.95	175	140	15.13%	Accepta ble	11.11%	Accepta ble	33.24%	Accepta ble	1.95%	Accepta ble	2.01%	Accepta ble	1.75%	Accepta ble	33.24%	Accepta ble
27.23	150	165	12.71%	Accepta ble	11.00%	Accepta ble	23.69%	Accepta ble	1.93%	Accepta ble	1.78%	Accepta ble	1.89%	Accepta ble	23.69%	Accepta ble
27.91	175	145	14.11%	Accepta ble	10.73%	Accepta ble	29.92%	Accepta ble	1.88%	Accepta ble	1.89%	Accepta ble	1.69%	Accepta ble	29.92%	Accepta ble
28.88	175	150	13.18%	Accepta ble	10.37%	Accepta ble	27.02%	Accepta ble	1.82%	Accepta ble	1.78%	Accepta ble	1.63%	Accepta ble	27.02%	Accepta ble
29.84	175	155	12.35%	Accepta ble	10.03%	Accepta ble	24.49%	Accepta ble	1.76%	Accepta ble	1.68%	Accepta ble	1.58%	Accepta ble	24.49%	Accepta ble

Optimisation results for timber frame, European Spruce

Weight (kg)	Width (mm)	Thickne ss (mm)	Bending Util (%)	Bending Status	Shear Util (%)	Shear Status	SLS Util (%)	SLS Status	Compre ssion Util (%)	Compre ssion Status	Bucklin g Util Y (%)	Bucklin g Status Y	Bucklin g Util Z (%)	Bucklin g Status Z	Final Util (%)	Final Status
8.36	95	100	74.59%	Accepta ble	44.33%	Accepta ble	210.80 %	Unacce ptable	6.02%	Accepta ble	9.91%	Accepta ble	10.78%	Accepta ble	210.80 %	Unacce ptable
8.80	100	100	70.86%	Accepta ble	42.11%	Accepta ble	200.26 %	Unacce ptable	5.72%	Accepta ble	9.41%	Accepta ble	9.41%	Accepta ble	200.26 %	Unacce ptable
9.20	95	110	61.64%	Accepta ble	40.30%	Accepta ble	158.38 %	Unacce ptable	5.47%	Accepta ble	7.77%	Accepta ble	9.80%	Accepta ble	158.38 %	Unacce ptable
9.61	95	115	56.40%	Accepta ble	38.55%	Accepta ble	138.60 %	Unacce ptable	5.24%	Accepta ble	6.97%	Accepta ble	9.38%	Accepta ble	138.60 %	Unacce ptable
9.68	100	110	58.56%	Accepta ble	38.28%	Accepta ble	150.46 %	Unacce ptable	5.20%	Accepta ble	7.38%	Accepta ble	8.56%	Accepta ble	150.46 %	Unacce ptable
10.03	95	120	51.80%	Accepta ble	36.94%	Accepta ble	121.99 %	Unacce ptable	5.02%	Accepta ble	6.30%	Accepta ble	8.99%	Accepta ble	121.99 %	Unacce ptable
10.12	100	115	53.58%	Accepta ble	36.62%	Accepta ble	131.67 %	Unacce ptable	4.97%	Accepta ble	6.62%	Accepta ble	8.19%	Accepta ble	131.67 %	Unacce ptable
10.12	115	100	61.61%	Accepta ble	36.62%	Accepta ble	174.14 %	Unacce ptable	4.97%	Accepta ble	8.19%	Accepta ble	6.62%	Accepta ble	174.14 %	Unacce ptable
10.45	95	125	47.74%	Accepta ble	35.46%	Accepta ble	107.93 %	Unacce ptable	4.82%	Accepta ble	5.75%	Accepta ble	8.63%	Accepta ble	107.93 %	Unacce ptable
10.56	100	120	49.21%	Accepta ble	35.09%	Accepta ble	115.89 %	Unacce ptable	4.77%	Accepta ble	5.99%	Accepta ble	7.85%	Accepta ble	115.89 %	Unacce ptable
10.87	95	130	44.13%	Accepta ble	34.10%	Accepta ble	95.95%	Accepta ble	4.63%	Accepta ble	5.28%	Accepta ble	8.29%	Accepta ble	95.95%	Accepta ble
11.00	100	125	45.35%	Accepta ble	33.69%	Accepta ble	102.53 %	Unacce ptable	4.58%	Accepta ble	5.46%	Accepta ble	7.53%	Accepta ble	102.53 %	Unacce ptable
11.00	125	100	56.69%	Accepta ble	33.69%	Accepta ble	160.21 %	Unacce ptable	4.58%	Accepta ble	7.53%	Accepta ble	5.46%	Accepta ble	160.21 %	Unacce ptable
11.13	115	110	50.92%	Accepta ble	33.29%	Accepta ble	130.83 %	Unacce ptable	4.52%	Accepta ble	6.42%	Accepta ble	6.02%	Accepta ble	130.83 %	Unacce ptable

11.29	95	135	40.93%	Accepta ble	32.84%	Accepta ble	85.68%	Accepta ble	4.46%	Accepta ble	4.88%	Accepta ble	7.99%	Accepta ble	85.68%	Accepta ble
11.44	100	130	41.93%	Accepta ble	32.39%	Accepta ble	91.15%	Accepta ble	4.40%	Accepta ble	5.01%	Accepta ble	7.24%	Accepta ble	91.15%	Accepta ble
11.64	115	115	46.59%	Accepta ble	31.84%	Accepta ble	114.50 %	Unacce ptable	4.33%	Accepta ble	5.76%	Accepta ble	5.76%	Accepta ble	114.50 %	Unacce ptable
11.70	95	140	38.05%	Accepta ble	31.66%	Accepta ble	76.82%	Accepta ble	4.30%	Accepta ble	4.54%	Accepta ble	7.70%	Accepta ble	76.82%	Accepta ble
11.88	100	135	38.88%	Accepta ble	31.19%	Accepta ble	81.39%	Accepta ble	4.24%	Accepta ble	4.63%	Accepta ble	6.97%	Accepta ble	81.39%	Accepta ble
12.10	125	110	46.85%	Accepta ble	30.63%	Accepta ble	120.37 %	Unacce ptable	4.16%	Accepta ble	5.90%	Accepta ble	4.96%	Accepta ble	120.37 %	Unacce ptable
12.12	95	145	35.48%	Accepta ble	30.57%	Accepta ble	69.15%	Accepta ble	4.15%	Accepta ble	4.25%	Accepta ble	7.44%	Accepta ble	69.15%	Accepta ble
12.14	115	120	42.79%	Accepta ble	30.52%	Accepta ble	100.77 %	Unacce ptable	4.14%	Accepta ble	5.21%	Accepta ble	5.52%	Accepta ble	100.77 %	Unacce ptable
12.14	138	100	51.35%	Accepta ble	30.52%	Accepta ble	145.11 %	Unacce ptable	4.14%	Accepta ble	6.82%	Accepta ble	4.44%	Accepta ble	145.11 %	Unacce ptable
12.32	100	140	36.15%	Accepta ble	30.08%	Accepta ble	72.98%	Accepta ble	4.09%	Accepta ble	4.31%	Accepta ble	6.72%	Accepta ble	72.98%	Accepta ble
12.54	95	150	33.15%	Accepta ble	29.55%	Accepta ble	62.46%	Accepta ble	4.01%	Accepta ble	3.99%	Accepta ble	7.19%	Accepta ble	62.46%	Accepta ble
12.65	115	125	39.43%	Accepta ble	29.30%	Accepta ble	89.16%	Accepta ble	3.98%	Accepta ble	4.75%	Accepta ble	5.30%	Accepta ble	89.16%	Accepta ble
12.65	125	115	42.86%	Accepta ble	29.30%	Accepta ble	105.34 %	Unacce ptable	3.98%	Accepta ble	5.30%	Accepta ble	4.75%	Accepta ble	105.34 %	Unacce ptable
12.76	100	145	33.70%	Accepta ble	29.04%	Accepta ble	65.69%	Accepta ble	3.94%	Accepta ble	4.03%	Accepta ble	6.49%	Accepta ble	65.69%	Accepta ble
12.96	95	155	31.05%	Accepta ble	28.60%	Accepta ble	56.61%	Accepta ble	3.88%	Accepta ble	3.77%	Accepta ble	6.96%	Accepta ble	56.61%	Accepta ble
13.16	115	130	36.46%	Accepta ble	28.17%	Accepta ble	79.26%	Accepta ble	3.83%	Accepta ble	4.36%	Accepta ble	5.09%	Accepta ble	79.26%	Accepta ble
13.20	100	150	31.49%	Accepta ble	28.08%	Accepta ble	59.34%	Accepta ble	3.81%	Accepta ble	3.79%	Accepta ble	6.28%	Accepta ble	59.34%	Accepta ble
13.20	125	120	39.37%	Accepta ble	28.08%	Accepta ble	92.71%	Accepta ble	3.81%	Accepta ble	4.79%	Accepta ble	4.55%	Accepta ble	92.71%	Accepta ble

13.20	150	100	47.24%	Accepta	28.08%	Accepta	133.51 %	Unacce	3.81%	Accepta	6.28%	Accepta	3.79%	Accepta	133.51 %	Unacce
				ble		ble	70	ptable		ble		ble		ble	%	ptable
13.36	138	110	42.43%	Accepta ble	27.74%	Accepta ble	109.03 %	Unacce ptable	3.77%	Accepta ble	5.35%	Accepta ble	4.03%	Accepta ble	109.03 %	Unacce ptable
13.38	95	160	29.14%	Accepta ble	27.71%	Accepta ble	51.46%	Accepta ble	3.76%	Accepta ble	3.58%	Accepta ble	6.74%	Accepta ble	51.46%	Accepta ble
13.64	100	155	29.49%	Accepta ble	27.17%	Accepta ble	53.78%	Accepta ble	3.69%	Accepta ble	3.59%	Accepta ble	6.07%	Accepta ble	53.78%	Accepta ble
13.66	115	135	33.81%	Accepta ble	27.13%	Accepta ble	70.78%	Accepta ble	3.68%	Accepta ble	4.03%	Accepta ble	4.90%	Accepta ble	70.78%	Accepta ble
13.75	125	125	36.28%	Accepta ble	26.95%	Accepta ble	82.03%	Accepta ble	3.66%	Accepta ble	4.37%	Accepta ble	4.37%	Accepta ble	82.03%	Accepta ble
13.79	95	165	27.40%	Accepta ble	26.87%	Accepta ble	46.93%	Accepta ble	3.65%	Accepta ble	3.41%	Accepta ble	6.54%	Accepta ble	46.93%	Accepta ble
13.97	138	115	38.82%	Accepta ble	26.54%	Accepta ble	95.42%	Accepta ble	3.60%	Accepta ble	4.80%	Accepta ble	3.86%	Accepta ble	95.42%	Accepta ble
14.08	100	160	27.68%	Accepta ble	26.32%	Accepta ble	48.89%	Accepta ble	3.57%	Accepta ble	3.40%	Accepta ble	5.88%	Accepta ble	48.89%	Accepta ble
14.17	115	140	31.44%	Accepta ble	26.16%	Accepta ble	63.46%	Accepta ble	3.55%	Accepta ble	3.75%	Accepta ble	4.73%	Accepta ble	63.46%	Accepta ble
14.30	125	130	33.54%	Accepta ble	25.92%	Accepta ble	72.92%	Accepta ble	3.52%	Accepta ble	4.01%	Accepta ble	4.20%	Accepta ble	72.92%	Accepta ble
14.52	100	165	26.03%	Accepta ble	25.52%	Accepta ble	44.58%	Accepta ble	3.47%	Accepta ble	3.24%	Accepta ble	5.71%	Accepta ble	44.58%	Accepta ble
14.52	150	110	39.04%	Accepta ble	25.52%	Accepta ble	100.30 %	Unacce ptable	3.47%	Accepta ble	4.92%	Accepta ble	3.45%	Accepta ble	100.30 %	Unacce ptable
14.57	138	120	35.66%	Accepta ble	25.43%	Accepta ble	83.98%	Accepta ble	3.45%	Accepta ble	4.34%	Accepta ble	3.70%	Accepta ble	83.98%	Accepta ble
14.67	115	145	29.31%	Accepta ble	25.26%	Accepta ble	57.12%	Accepta ble	3.43%	Accepta ble	3.51%	Accepta ble	4.57%	Accepta ble	57.12%	Accepta ble
14.85	125	135	31.10%	Accepta ble	24.96%	Accepta ble	65.11%	Accepta ble	3.39%	Accepta ble	3.71%	Accepta ble	4.04%	Accepta ble	65.11%	Accepta ble
15.18	115	150	27.38%	Accepta ble	24.41%	Accepta ble	51.60%	Accepta ble	3.32%	Accepta ble	3.30%	Accepta ble	4.41%	Accepta ble	51.60%	Accepta ble
15.18	138	125	32.86%	Accepta ble	24.41%	Accepta ble	74.30%	Accepta ble	3.32%	Accepta ble	3.96%	Accepta ble	3.55%	Accepta ble	74.30%	Accepta ble

15.18	150	115	35.72%	Accepta ble	24.41%	Accepta ble	87.78%	Accepta ble	3.32%	Accepta ble	4.41%	Accepta ble	3.30%	Accepta ble	87.78%	Accepta ble
15.40	175	100	40.49%	Accepta ble	24.06%	Accepta ble	114.43 %	Unacce ptable	3.27%	Accepta ble	5.38%	Accepta ble	2.96%	Accepta ble	114.43 %	Unacce ptable
15.40	125	140	28.92%	Accepta ble	24.06%	Accepta ble	58.38%	Accepta ble	3.27%	Accepta ble	3.45%	Accepta ble	3.90%	Accepta ble	58.38%	Accepta ble
15.69	115	155	25.65%	Accepta ble	23.63%	Accepta ble	46.76%	Accepta ble	3.21%	Accepta ble	3.12%	Accepta ble	4.27%	Accepta ble	46.76%	Accepta ble
15.79	138	130	30.38%	Accepta ble	23.47%	Accepta ble	66.05%	Accepta ble	3.19%	Accepta ble	3.63%	Accepta ble	3.41%	Accepta ble	66.05%	Accepta ble
15.84	150	120	32.80%	Accepta ble	23.40%	Accepta ble	77.26%	Accepta ble	3.18%	Accepta ble	3.99%	Accepta ble	3.16%	Accepta ble	77.26%	Accepta ble
15.95	125	145	26.96%	Accepta ble	23.23%	Accepta ble	52.55%	Accepta ble	3.16%	Accepta ble	3.23%	Accepta ble	3.76%	Accepta ble	52.55%	Accepta ble
16.19	115	160	24.07%	Accepta ble	22.89%	Accepta ble	42.51%	Accepta ble	3.11%	Accepta ble	2.96%	Accepta ble	4.14%	Accepta ble	42.51%	Accepta ble
16.39	138	135	28.17%	Accepta ble	22.61%	Accepta ble	58.98%	Accepta ble	3.07%	Accepta ble	3.36%	Accepta ble	3.29%	Accepta ble	58.98%	Accepta ble
16.50	125	150	25.19%	Accepta ble	22.46%	Accepta ble	47.47%	Accepta ble	3.05%	Accepta ble	3.04%	Accepta ble	3.64%	Accepta ble	47.47%	Accepta ble
16.50	150	125	30.23%	Accepta ble	22.46%	Accepta ble	68.35%	Accepta ble	3.05%	Accepta ble	3.64%	Accepta ble	3.04%	Accepta ble	68.35%	Accepta ble
16.70	115	165	22.63%	Accepta ble	22.19%	Accepta ble	38.76%	Accepta ble	3.01%	Accepta ble	2.82%	Accepta ble	4.01%	Accepta ble	38.76%	Accepta ble
16.94	175	110	33.46%	Accepta ble	21.88%	Accepta ble	85.98%	Accepta ble	2.97%	Accepta ble	4.22%	Accepta ble	2.69%	Accepta ble	85.98%	Accepta ble
17.00	138	140	26.20%	Accepta ble	21.80%	Accepta ble	52.88%	Accepta ble	2.96%	Accepta ble	3.12%	Accepta ble	3.17%	Accepta ble	52.88%	Accepta ble
17.05	125	155	23.59%	Accepta ble	21.74%	Accepta ble	43.02%	Accepta ble	2.95%	Accepta ble	2.87%	Accepta ble	3.52%	Accepta ble	43.02%	Accepta ble
17.16	150	130	27.95%	Accepta ble	21.60%	Accepta ble	60.77%	Accepta ble	2.93%	Accepta ble	3.34%	Accepta ble	2.92%	Accepta ble	60.77%	Accepta ble
17.60	125	160	22.14%	Accepta ble	21.06%	Accepta ble	39.11%	Accepta ble	2.86%	Accepta ble	2.72%	Accepta ble	3.41%	Accepta ble	39.11%	Accepta ble
17.61	138	145	24.42%	Accepta ble	21.05%	Accepta ble	47.60%	Accepta ble	2.86%	Accepta ble	2.92%	Accepta ble	3.06%	Accepta ble	47.60%	Accepta ble

17.71	175	115	30.62%	Accepta ble	20.93%	Accepta ble	75.24%	Accepta ble	2.84%	Accepta ble	3.78%	Accepta ble	2.58%	Accepta ble	75.24%	Accepta ble
17.82	150	135	25.92%	Accepta ble	20.80%	Accepta ble	54.26%	Accepta ble	2.82%	Accepta ble	3.09%	Accepta ble	2.81%	Accepta ble	54.26%	Accepta ble
18.15	125	165	20.82%	Accepta ble	20.42%	Accepta ble	35.66%	Accepta ble	2.77%	Accepta ble	2.59%	Accepta ble	3.31%	Accepta ble	35.66%	Accepta ble
18.22	138	150	22.82%	Accepta ble	20.34%	Accepta ble	43.00%	Accepta ble	2.76%	Accepta ble	2.75%	Accepta ble	2.96%	Accepta ble	43.00%	Accepta ble
18.48	175	120	28.12%	Accepta ble	20.05%	Accepta ble	66.22%	Accepta ble	2.72%	Accepta ble	3.42%	Accepta ble	2.47%	Accepta ble	66.22%	Accepta ble
18.48	150	140	24.10%	Accepta ble	20.05%	Accepta ble	48.65%	Accepta ble	2.72%	Accepta ble	2.87%	Accepta ble	2.71%	Accepta ble	48.65%	Accepta ble
18.82	138	155	21.37%	Accepta ble	19.69%	Accepta ble	38.97%	Accepta ble	2.67%	Accepta ble	2.60%	Accepta ble	2.86%	Accepta ble	38.97%	Accepta ble
19.14	150	145	22.47%	Accepta ble	19.36%	Accepta ble	43.79%	Accepta ble	2.63%	Accepta ble	2.69%	Accepta ble	2.62%	Accepta ble	43.79%	Accepta ble
19.25	175	125	25.91%	Accepta ble	19.25%	Accepta ble	58.59%	Accepta ble	2.61%	Accepta ble	3.12%	Accepta ble	2.37%	Accepta ble	58.59%	Accepta ble
19.43	138	160	20.06%	Accepta ble	19.07%	Accepta ble	35.43%	Accepta ble	2.59%	Accepta ble	2.46%	Accepta ble	2.77%	Accepta ble	35.43%	Accepta ble
19.80	150	150	20.99%	Accepta ble	18.72%	Accepta ble	39.56%	Accepta ble	2.54%	Accepta ble	2.53%	Accepta ble	2.53%	Accepta ble	39.56%	Accepta ble
20.02	175	130	23.96%	Accepta ble	18.51%	Accepta ble	52.09%	Accepta ble	2.51%	Accepta ble	2.86%	Accepta ble	2.28%	Accepta ble	52.09%	Accepta ble
20.04	138	165	18.86%	Accepta ble	18.50%	Accepta ble	32.30%	Accepta ble	2.51%	Accepta ble	2.35%	Accepta ble	2.69%	Accepta ble	32.30%	Accepta ble
20.46	150	155	19.66%	Accepta ble	18.11%	Accepta ble	35.85%	Accepta ble	2.46%	Accepta ble	2.39%	Accepta ble	2.45%	Accepta ble	35.85%	Accepta ble
20.79	175	135	22.22%	Accepta ble	17.83%	Accepta ble	46.51%	Accepta ble	2.42%	Accepta ble	2.65%	Accepta ble	2.19%	Accepta ble	46.51%	Accepta ble
21.12	150	160	18.45%	Accepta ble	17.55%	Accepta ble	32.59%	Accepta ble	2.38%	Accepta ble	2.27%	Accepta ble	2.37%	Accepta ble	32.59%	Accepta ble
21.56	175	140	20.66%	Accepta ble	17.19%	Accepta ble	41.70%	Accepta ble	2.33%	Accepta ble	2.46%	Accepta ble	2.12%	Accepta ble	41.70%	Accepta ble
21.78	150	165	17.35%	Accepta ble	17.02%	Accepta ble	29.72%	Accepta ble	2.31%	Accepta ble	2.16%	Accepta ble	2.30%	Accepta ble	29.72%	Accepta ble

22.33	175	145	19.26%	Accepta ble	16.60%	Accepta ble	37.54%	Accepta ble	2.25%	Accepta ble	2.31%	Accepta ble	2.04%	Accepta ble	37.54%	Accepta ble
23.10	175	150	18.00%	Accepta ble	16.04%	Accepta ble	33.91%	Accepta ble	2.18%	Accepta ble	2.17%	Accepta ble	1.97%	Accepta ble	33.91%	Accepta ble
23.87	175	155	16.85%	Accepta ble	15.53%	Accepta ble	30.73%	Accepta ble	2.11%	Accepta ble	2.05%	Accepta ble	1.91%	Accepta ble	30.73%	Accepta ble
24.64	175	160	15.82%	Accepta ble	15.04%	Accepta ble	27.94%	Accepta ble	2.04%	Accepta ble	1.94%	Accepta ble	1.85%	Accepta ble	27.94%	Accepta ble
25.41	175	165	14.87%	Accepta ble	14.58%	Accepta ble	25.47%	Accepta ble	1.98%	Accepta ble	1.85%	Accepta ble	1.79%	Accepta ble	25.47%	Accepta ble

Optimisation results for timber frame, European Larch

Weight (kg)	Width (mm)	Thickne ss (mm)	Bending Util (%)	Bending Status	Shear Util (%)	Shear Status	SLS Util (%)	SLS Status	Compre ssion Util (%)	Compre ssion Status	Bucklin g Util Y (%)	Bucklin g Status Y	Bucklin g Util Z (%)	Bucklin g Status Z	Final Util (%)	Final Status
11.59	95	100	51.64%	Accepta ble	26.11%	Accepta ble	182.57 %	Unacce ptable	4.68%	Accepta ble	8.42%	Accepta ble	9.19%	Accepta ble	182.57 %	Unacce ptable
12.20	100	100	49.05%	Accepta ble	24.80%	Accepta ble	173.44 %	Unacce ptable	4.45%	Accepta ble	8.00%	Accepta ble	8.00%	Accepta ble	173.44 %	Unacce ptable
12.75	95	110	42.68%	Accepta ble	23.73%	Accepta ble	137.16 %	Unacce ptable	4.26%	Accepta ble	6.56%	Accepta ble	8.35%	Accepta ble	137.16 %	Unacce ptable
13.33	95	115	39.04%	Accepta ble	22.70%	Accepta ble	120.04 %	Unacce ptable	4.07%	Accepta ble	5.86%	Accepta ble	7.99%	Accepta ble	120.04 %	Unacce ptable
13.42	100	110	40.54%	Accepta ble	22.55%	Accepta ble	130.31 %	Unacce ptable	4.04%	Accepta ble	6.23%	Accepta ble	7.27%	Accepta ble	130.31 %	Unacce ptable
13.91	95	120	35.86%	Accepta ble	21.75%	Accepta ble	105.65 %	Unacce ptable	3.90%	Accepta ble	5.28%	Accepta ble	7.66%	Accepta ble	105.65 %	Unacce ptable
14.03	100	115	37.09%	Accepta ble	21.57%	Accepta ble	114.04 %	Unacce ptable	3.87%	Accepta ble	5.57%	Accepta ble	6.96%	Accepta ble	114.04 %	Unacce ptable
14.03	115	100	42.66%	Accepta ble	21.57%	Accepta ble	150.82 %	Unacce ptable	3.87%	Accepta ble	6.96%	Accepta ble	5.57%	Accepta ble	150.82 %	Unacce ptable
14.49	95	125	33.05%	Accepta ble	20.88%	Accepta ble	93.47%	Accepta ble	3.75%	Accepta ble	4.79%	Accepta ble	7.35%	Accepta ble	93.47%	Accepta ble
14.64	100	120	34.07%	Accepta ble	20.67%	Accepta ble	100.37 %	Unacce ptable	3.71%	Accepta ble	5.01%	Accepta ble	6.67%	Accepta ble	100.37 %	Unacce ptable
15.07	95	130	30.55%	Accepta ble	20.08%	Accepta ble	83.10%	Accepta ble	3.60%	Accepta ble	4.38%	Accepta ble	7.07%	Accepta ble	83.10%	Accepta ble

15.25	100	125	31.40%	Accepta ble	19.84%	Accepta ble	88.80%	Accepta ble	3.56%	Accepta ble	4.55%	Accepta ble	6.40%	Accepta ble	88.80%	Accepta ble
15.25	125	100	39.24%	Accepta ble	19.84%	Accepta ble	138.75 %	Unacce ptable	3.56%	Accepta ble	6.40%	Accepta ble	4.55%	Accepta ble	138.75 %	Unacce ptable
15.43	115	110	35.25%	Accepta ble	19.60%	Accepta ble	113.31 %	Unacce ptable	3.52%	Accepta ble	5.42%	Accepta ble	5.06%	Accepta ble	113.31 %	Unacce ptable
15.65	95	135	28.33%	Accepta ble	19.34%	Accepta ble	74.20%	Accepta ble	3.47%	Accepta ble	4.03%	Accepta ble	6.81%	Accepta ble	74.20%	Accepta ble
15.86	100	130	29.03%	Accepta ble	19.08%	Accepta ble	78.94%	Accepta ble	3.42%	Accepta ble	4.16%	Accepta ble	6.15%	Accepta ble	78.94%	Accepta ble
16.13	115	115	32.25%	Accepta ble	18.75%	Accepta ble	99.16%	Accepta ble	3.36%	Accepta ble	4.84%	Accepta ble	4.84%	Accepta ble	99.16%	Accepta ble
16.23	95	140	26.35%	Accepta ble	18.65%	Accepta ble	66.53%	Accepta ble	3.35%	Accepta ble	3.73%	Accepta ble	6.56%	Accepta ble	66.53%	Accepta ble
16.47	100	135	26.92%	Accepta ble	18.37%	Accepta ble	70.49%	Accepta ble	3.30%	Accepta ble	3.82%	Accepta ble	5.93%	Accepta ble	70.49%	Accepta ble
16.77	125	110	32.43%	Accepta ble	18.04%	Accepta ble	104.24 %	Unacce ptable	3.24%	Accepta ble	4.98%	Accepta ble	4.14%	Accepta ble	104.24 %	Unacce ptable
16.81	95	145	24.56%	Accepta ble	18.00%	Accepta ble	59.88%	Accepta ble	3.23%	Accepta ble	3.47%	Accepta ble	6.34%	Accepta ble	59.88%	Accepta ble
16.84	115	120	29.62%	Accepta ble	17.97%	Accepta ble	87.28%	Accepta ble	3.22%	Accepta ble	4.36%	Accepta ble	4.64%	Accepta ble	87.28%	Accepta ble
16.84	138	100	35.55%	Accepta ble	17.97%	Accepta ble	125.68 %	Unacce ptable	3.22%	Accepta ble	5.80%	Accepta ble	3.65%	Accepta ble	125.68 %	Unacce ptable
17.08	100	140	25.03%	Accepta ble	17.71%	Accepta ble	63.21%	Accepta ble	3.18%	Accepta ble	3.54%	Accepta ble	5.71%	Accepta ble	63.21%	Accepta ble
17.38	95	150	22.95%	Accepta ble	17.40%	Accepta ble	54.09%	Accepta ble	3.12%	Accepta ble	3.25%	Accepta ble	6.13%	Accepta ble	54.09%	Accepta ble
17.54	115	125	27.30%	Accepta ble	17.25%	Accepta ble	77.22%	Accepta ble	3.09%	Accepta ble	3.96%	Accepta ble	4.45%	Accepta ble	77.22%	Accepta ble
17.54	125	115	29.67%	Accepta ble	17.25%	Accepta ble	91.23%	Accepta ble	3.09%	Accepta ble	4.45%	Accepta ble	3.96%	Accepta ble	91.23%	Accepta ble
17.69	100	145	23.33%	Accepta ble	17.10%	Accepta ble	56.89%	Accepta ble	3.07%	Accepta ble	3.30%	Accepta ble	5.52%	Accepta ble	56.89%	Accepta ble
17.96	95	155	21.49%	Accepta ble	16.84%	Accepta ble	49.03%	Accepta ble	3.02%	Accepta ble	3.06%	Accepta ble	5.93%	Accepta ble	49.03%	Accepta ble
18.24	115	130	25.24%	Accepta ble	16.59%	Accepta ble	68.65%	Accepta ble	2.98%	Accepta ble	3.61%	Accepta ble	4.28%	Accepta ble	68.65%	Accepta ble
18.30	100	150	21.80%	Accepta ble	16.53%	Accepta ble	51.39%	Accepta ble	2.97%	Accepta ble	3.09%	Accepta ble	5.33%	Accepta ble	51.39%	Accepta ble
18.30	125	120	27.25%	Accepta ble	16.53%	Accepta ble	80.30%	Accepta ble	2.97%	Accepta ble	4.01%	Accepta ble	3.79%	Accepta ble	80.30%	Accepta ble
18.30	150	100	32.70%	Accepta ble	16.53%	Accepta ble	115.62 %	Unacce ptable	2.97%	Accepta ble	5.33%	Accepta ble	3.09%	Accepta ble	115.62 %	Unacce ptable

10 50	100	110			16.04%		0.4.40%		0.00%		4 510		0.00%		0.4.400/	
18.52	138	110	29.38%	Accepta ble	16.34%	Accepta ble	94.42%	Accepta ble	2.93%	Accepta ble	4.51%	Accepta ble	3.32%	Accepta ble	94.42%	Accepta ble
18.54	95	160	20.17%	Accepta ble	16.32%	Accepta ble	44.57%	Accepta ble	2.93%	Accepta ble	2.89%	Accepta ble	5.74%	Accepta ble	44.57%	Accepta ble
18.91	100	155	20.42%	Accepta ble	16.00%	Accepta ble	46.57%	Accepta ble	2.87%	Accepta ble	2.90%	Accepta ble	5.16%	Accepta ble	46.57%	Accepta ble
18.94	115	135	23.41%	Accepta ble	15.97%	Accepta ble	61.30%	Accepta ble	2.87%	Accepta ble	3.33%	Accepta ble	4.12%	Accepta ble	61.30%	Accepta ble
19.06	125	125	25.12%	Accepta ble	15.87%	Accepta ble	71.04%	Accepta ble	2.85%	Accepta ble	3.64%	Accepta ble	3.64%	Accepta ble	71.04%	Accepta ble
19.12	95	165	18.97%	Accepta ble	15.82%	Accepta ble	40.64%	Accepta ble	2.84%	Accepta ble	2.74%	Accepta ble	5.57%	Accepta ble	40.64%	Accepta ble
19.36	138	115	26.88%	Accepta ble	15.63%	Accepta ble	82.64%	Accepta ble	2.80%	Accepta ble	4.03%	Accepta ble	3.17%	Accepta ble	82.64%	Accepta ble
19.52	100	160	19.16%	Accepta ble	15.50%	Accepta ble	42.34%	Accepta ble	2.78%	Accepta ble	2.74%	Accepta ble	5.00%	Accepta ble	42.34%	Accepta ble
19.64	115	140	21.76%	Accepta ble	15.40%	Accepta ble	54.96%	Accepta ble	2.76%	Accepta ble	3.08%	Accepta ble	3.98%	Accepta ble	54.96%	Accepta ble
19.82	125	130	23.22%	Accepta ble	15.26%	Accepta ble	63.15%	Accepta ble	2.74%	Accepta ble	3.33%	Accepta ble	3.50%	Accepta ble	63.15%	Accepta ble
20.13	100	165	18.02%	Accepta ble	15.03%	Accepta ble	38.61%	Accepta ble	2.70%	Accepta ble	2.60%	Accepta ble	4.85%	Accepta ble	38.61%	Accepta ble
20.13	150	110	27.03%	Accepta ble	15.03%	Accepta ble	86.87%	Accepta ble	2.70%	Accepta ble	4.15%	Accepta ble	2.81%	Accepta ble	86.87%	Accepta ble
20.20	138	120	24.69%	Accepta ble	14.98%	Accepta ble	72.73%	Accepta ble	2.69%	Accepta ble	3.63%	Accepta ble	3.04%	Accepta ble	72.73%	Accepta ble
20.34	115	145	20.29%	Accepta ble	14.87%	Accepta ble	49.47%	Accepta ble	2.67%	Accepta ble	2.87%	Accepta ble	3.84%	Accepta ble	49.47%	Accepta ble
20.59	125	135	21.53%	Accepta ble	14.70%	Accepta ble	56.39%	Accepta ble	2.64%	Accepta ble	3.06%	Accepta ble	3.37%	Accepta ble	56.39%	Accepta ble
21.05	115	150	18.96%	Accepta ble	14.38%	Accepta ble	44.69%	Accepta ble	2.58%	Accepta ble	2.68%	Accepta ble	3.71%	Accepta ble	44.69%	Accepta ble
21.05	138	125	22.75%	Accepta ble	14.38%	Accepta ble	64.35%	Accepta ble	2.58%	Accepta ble	3.30%	Accepta ble	2.92%	Accepta ble	64.35%	Accepta ble
21.05	150	115	24.73%	Accepta ble	14.38%	Accepta ble	76.03%	Accepta ble	2.58%	Accepta ble	3.71%	Accepta ble	2.68%	Accepta ble	76.03%	Accepta ble
21.35	175	100	28.03%	Accepta ble	14.17%	Accepta ble	99.11%	Accepta ble	2.54%	Accepta ble	4.57%	Accepta ble	2.37%	Accepta ble	99.11%	Accepta ble
21.35	125	140	20.02%	Accepta ble	14.17%	Accepta ble	50.56%	Accepta ble	2.54%	Accepta ble	2.83%	Accepta ble	3.25%	Accepta ble	50.56%	Accepta ble
21.75	115	155	17.76%	Accepta ble	13.91%	Accepta ble	40.50%	Accepta ble	2.50%	Accepta ble	2.53%	Accepta ble	3.59%	Accepta ble	40.50%	Accepta ble
21.89	138	130	21.03%	Accepta ble	13.82%	Accepta ble	57.20%	Accepta ble	2.48%	Accepta ble	3.01%	Accepta ble	2.81%	Accepta ble	57.20%	Accepta ble

21.96	150	120	22.71%	Accepta	13.78%	Accepta	66.91%	Accepta	2.47%	Accepta	3.34%	Accepta	2.57%	Accepta	66.91%	Accepta
-		-		ble		ble		ble		ble		ble		ble		ble
22.11	125	145	18.67%	Accepta ble	13.68%	Accepta ble	45.51%	Accepta ble	2.45%	Accepta ble	2.64%	Accepta ble	3.14%	Accepta ble	45.51%	Accepta ble
22.45	115	160	16.66%	Accepta ble	13.48%	Accepta ble	36.82%	Accepta ble	2.42%	Accepta ble	2.39%	Accepta ble	3.48%	Accepta ble	36.82%	Accepta ble
22.73	138	135	19.50%	Accepta ble	13.31%	Accepta ble	51.08%	Accepta ble	2.39%	Accepta ble	2.77%	Accepta ble	2.70%	Accepta ble	51.08%	Accepta ble
22.88	125	150	17.44%	Accepta ble	13.23%	Accepta ble	41.11%	Accepta ble	2.37%	Accepta ble	2.47%	Accepta ble	3.03%	Accepta ble	41.11%	Accepta ble
22.88	150	125	20.93%	Accepta ble	13.23%	Accepta ble	59.20%	Accepta ble	2.37%	Accepta ble	3.03%	Accepta ble	2.47%	Accepta ble	59.20%	Accepta ble
23.15	115	165	15.67%	Accepta ble	13.07%	Accepta ble	33.57%	Accepta ble	2.34%	Accepta ble	2.26%	Accepta ble	3.37%	Accepta ble	33.57%	Accepta ble
23.48	175	110	23.17%	Accepta ble	12.88%	Accepta ble	74.46%	Accepta ble	2.31%	Accepta ble	3.56%	Accepta ble	2.15%	Accepta ble	74.46%	Accepta ble
23.57	138	140	18.14%	Accepta ble	12.84%	Accepta ble	45.80%	Accepta ble	2.30%	Accepta ble	2.57%	Accepta ble	2.61%	Accepta ble	45.80%	Accepta ble
23.64	125	155	16.33%	Accepta ble	12.80%	Accepta ble	37.26%	Accepta ble	2.30%	Accepta ble	2.32%	Accepta ble	2.93%	Accepta ble	37.26%	Accepta ble
23.79	150	130	19.35%	Accepta ble	12.72%	Accepta ble	52.63%	Accepta ble	2.28%	Accepta ble	2.77%	Accepta ble	2.37%	Accepta ble	52.63%	Accepta ble
24.40	125	160	15.33%	Accepta ble	12.40%	Accepta ble	33.87%	Accepta ble	2.22%	Accepta ble	2.20%	Accepta ble	2.84%	Accepta ble	33.87%	Accepta ble
24.41	138	145	16.91%	Accepta ble	12.39%	Accepta ble	41.22%	Accepta ble	2.22%	Accepta ble	2.39%	Accepta ble	2.52%	Accepta ble	41.22%	Accepta ble
24.55	175	115	21.20%	Accepta ble	12.32%	Accepta ble	65.16%	Accepta ble	2.21%	Accepta ble	3.18%	Accepta ble	2.06%	Accepta ble	65.16%	Accepta ble
24.71	150	135	17.94%	Accepta ble	12.25%	Accepta ble	46.99%	Accepta ble	2.20%	Accepta ble	2.55%	Accepta ble	2.29%	Accepta ble	46.99%	Accepta ble
25.16	125	165	14.41%	Accepta ble	12.02%	Accepta ble	30.89%	Accepta ble	2.16%	Accepta ble	2.08%	Accepta ble	2.76%	Accepta ble	30.89%	Accepta ble
25.25	138	150	15.80%	Accepta ble	11.98%	Accepta ble	37.24%	Accepta ble	2.15%	Accepta ble	2.24%	Accepta ble	2.43%	Accepta ble	37.24%	Accepta ble
25.62	175	120	19.47%	Accepta ble	11.81%	Accepta ble	57.35%	Accepta ble	2.12%	Accepta ble	2.87%	Accepta ble	1.97%	Accepta ble	57.35%	Accepta ble
25.62	150	140	16.69%	Accepta ble	11.81%	Accepta ble	42.14%	Accepta ble	2.12%	Accepta ble	2.36%	Accepta ble	2.20%	Accepta ble	42.14%	Accepta ble
26.10	138	155	14.80%	Accepta ble	11.59%	Accepta ble	33.75%	Accepta ble	2.08%	Accepta ble	2.10%	Accepta ble	2.35%	Accepta ble	33.75%	Accepta ble
26.53	150	145	15.55%	Accepta ble	11.40%	Accepta ble	37.93%	Accepta ble	2.05%	Accepta ble	2.20%	Accepta ble	2.13%	Accepta ble	37.93%	Accepta ble
26.69	175	125	17.94%	Accepta ble	11.34%	Accepta ble	50.74%	Accepta ble	2.03%	Accepta ble	2.60%	Accepta ble	1.89%	Accepta ble	50.74%	Accepta ble

26.94	138	160	13.89%	Accepta	11.23%	Accepta	30.68%	Accepta	2.01%	Accepta	1.99%	Accepta	2.28%	Accepta	30.68%	Accepta
				ble		ble		ble		ble		ble		ble		ble
27.45	150	150	14.53%	Accepta ble	11.02%	Accepta ble	34.26%	Accepta ble	1.98%	Accepta ble	2.06%	Accepta ble	2.06%	Accepta ble	34.26%	Accepta ble
27.75	175	130	16.59%	Accepta ble	10.90%	Accepta ble	45.11%	Accepta ble	1.96%	Accepta ble	2.38%	Accepta ble	1.82%	Accepta ble	45.11%	Accepta ble
27.78	138	165	13.06%	Accepta ble	10.89%	Accepta ble	27.98%	Accepta ble	1.95%	Accepta ble	1.89%	Accepta ble	2.21%	Accepta ble	27.98%	Accepta ble
28.36	150	155	13.61%	Accepta ble	10.67%	Accepta ble	31.05%	Accepta ble	1.91%	Accepta ble	1.94%	Accepta ble	1.99%	Accepta ble	31.05%	Accepta ble
28.82	175	135	15.38%	Accepta ble	10.50%	Accepta ble	40.28%	Accepta ble	1.88%	Accepta ble	2.19%	Accepta ble	1.75%	Accepta ble	40.28%	Accepta ble
29.28	150	160	12.77%	Accepta ble	10.33%	Accepta ble	28.23%	Accepta ble	1.85%	Accepta ble	1.83%	Accepta ble	1.93%	Accepta ble	28.23%	Accepta ble
29.89	175	140	14.30%	Accepta ble	10.12%	Accepta ble	36.12%	Accepta ble	1.82%	Accepta ble	2.02%	Accepta ble	1.69%	Accepta ble	36.12%	Accepta ble
30.20	150	165	12.01%	Accepta ble	10.02%	Accepta ble	25.74%	Accepta ble	1.80%	Accepta ble	1.74%	Accepta ble	1.87%	Accepta ble	25.74%	Accepta ble
30.96	175	145	13.33%	Accepta ble	9.77%	Accepta ble	32.51%	Accepta ble	1.75%	Accepta ble	1.88%	Accepta ble	1.63%	Accepta ble	32.51%	Accepta ble
32.02	175	150	12.46%	Accepta ble	9.45%	Accepta ble	29.37%	Accepta ble	1.69%	Accepta ble	1.76%	Accepta ble	1.58%	Accepta ble	29.37%	Accepta ble
33.09	175	155	11.67%	Accepta ble	9.14%	Accepta ble	26.61%	Accepta ble	1.64%	Accepta ble	1.66%	Accepta ble	1.53%	Accepta ble	26.61%	Accepta ble

Optimisation results for PMT Joints based on Equivalent Steel Bolt Method

Diameter(mm)	L.e(mm)	L.s(mm)	L.v(mm)	L.g(mm)	Joint capacity(kN)	Joint Status
12.7	14.69	18.36	11.02	11.02	2.65	Not Acceptable
12.954	14.98	18.73	11.24	11.24	2.76	Not Acceptable
13.208	15.28	19.1	11.46	11.46	2.87	Not Acceptable
13.462	15.57	19.46	11.68	11.68	2.98	Not Acceptable
13.716	15.86	19.83	11.9	11.9	3.09	Not Acceptable

13.97	16.16	20.2	12.12	12.12	3.21	Not Acceptable
14.224	16.48	20.61	12.36	12.36	3.33	Not Acceptable
14.478	17.08	21.35	12.81	12.81	3.45	Not Acceptable
14.732	17.68	22.1	13.26	13.26	3.57	Not Acceptable
14.986	18.3	22.87	13.72	13.72	3.69	Not Acceptable
15.24	18.92	23.65	14.19	14.19	3.82	Not Acceptable
15.494	19.56	24.45	14.67	14.67	3.95	Not Acceptable
15.748	20.21	25.26	15.15	15.15	4.08	Not Acceptable
16.002	20.86	26.08	15.65	15.65	4.21	Not Acceptable
16.256	21.53	26.91	16.15	16.15	4.34	Not Acceptable
16.51	22.21	27.76	16.66	16.66	4.48	Not Acceptable
16.764	22.9	28.62	17.17	17.17	4.62	Acceptable
17.018	23.6	29.5	17.7	17.7	4.76	Acceptable
17.272	24.31	30.38	18.23	18.23	4.9	Acceptable
17.526	25.03	31.28	18.77	18.77	5.05	Acceptable
17.78	25.76	32.2	19.32	19.32	5.2	Acceptable
18.034	26.5	33.12	19.87	19.87	5.35	Acceptable
18.288	27.25	34.06	20.44	20.44	5.5	Acceptable
18.542	28.01	35.02	21.01	21.01	5.65	Acceptable
18.796	28.78	35.98	21.59	21.59	5.81	Acceptable
19.05	29.57	36.96	22.18	22.18	5.97	Acceptable

19.304	30.36	37.95	22.77	22.77	6.13	Acceptable
19.558	31.17	38.96	23.37	23.37	6.29	Acceptable
19.812	31.98	39.98	23.99	23.99	6.45	Acceptable
20.066	32.81	41.01	24.6	24.6	6.62	Acceptable
20.32	33.64	42.05	25.23	25.23	6.79	Acceptable
20.574	34.49	43.11	25.87	25.87	6.96	Acceptable
20.828	35.34	44.18	26.51	26.51	7.13	Acceptable
21.082	36.21	45.27	27.16	27.16	7.31	Acceptable
21.336	37.09	46.36	27.82	27.82	7.48	Acceptable
21.59	37.98	47.47	28.48	28.48	7.66	Acceptable
21.844	38.88	48.6	29.16	29.16	7.84	Acceptable
22.098	39.79	49.73	29.84	29.84	8.03	Acceptable
22.352	40.71	50.88	30.53	30.53	8.21	Acceptable
22.606	41.64	52.05	31.23	31.23	8.4	Acceptable
22.86	42.58	53.22	31.93	31.93	8.59	Acceptable
23.114	43.53	54.41	32.65	32.65	8.78	Acceptable
23.368	44.49	55.61	33.37	33.37	8.98	Acceptable
23.622	45.46	56.83	34.1	34.1	9.17	Acceptable
23.876	46.45	58.06	34.84	34.84	9.37	Acceptable
24.13	47.44	59.3	35.58	35.58	9.57	Acceptable
24.384	48.44	60.56	36.33	36.33	9.78	Acceptable

24.638	49.46	61.82	37.09	37.09	9.98	Acceptable
24.892	50.48	63.1	37.86	37.86	10.19	Acceptable
25.146	51.52	64.4	38.64	38.64	10.4	Acceptable
25.4	52.57	65.71	39.42	39.42	10.61	Acceptable
25.654	53.62	67.03	40.22	40.22	10.82	Acceptable
25.908	54.69	68.36	41.02	41.02	11.04	Acceptable
26.162	55.77	69.71	41.82	41.82	11.25	Acceptable
26.416	56.85	71.07	42.64	42.64	11.47	Acceptable
26.67	57.95	72.44	43.46	43.46	11.69	Not Acceptable
26.924	59.06	73.83	44.3	44.3	11.92	Not Acceptable

Input script optimisation of timber frames

```
from itertools import groupby
import numpy as np
import math as mt
import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import Axes3D
import matplotlib.colors as mcolors
import csv
def save_results_to_csv(results, filename="results.csv"):
  # Column headers for the CSV
  columns = ['Weight (kg)', 'Width (mm)', 'Thickness (mm)', 'Length (m)',
         'Bending Util (%)', 'Bending Status', 'Shear Util (%)', 'Shear Status',
         'SLS Util (%)', 'SLS Status', 'Compression Util (%)', 'Compression Status',
         'Buckling Util Y (%)', 'Buckling Status Y', 'Buckling Util Z (%)', 'Buckling Status Z',
         'Final Util (%)', 'Final Status']
  # Writing to CSV file
  with open(filename, mode='w', newline=") as file:
    writer = csv.writer(file)
    writer.writerow(columns) # Write the headers
    # Write the rows
    for result in results:
       writer.writerow([f"{result[0]:.2f}", f"{result[1]*1000:.0f}", f"{result[2]*1000:.0f}", f"{result[3]:.2f}",
                 f"{result[4]:.2f}%", result[5], f"{result[6]:.2f}%", result[7],
                 f"{result[8]:.2f}%", result[9], f"{result[10]:.2f}%", result[11],
                 f"{result[12]:.2f}%", result[13], f"{result[14]:.2f}%", result[15],
                 f"{result[16]:.2f}%", result[17]])
def plot_3d_surface_with_distinct_gradient_markers(results):
  # Convert results to numpy arrays for easier manipulation
  widths = np.array([result[1] for result in results])
  thicknesses = np.array([result[2] for result in results])
  weights = np.array([result[0] for result in results])
  utilizations = np.array([result[16] for result in results]) # Assuming the final utilization factor is at index 17
  # Normalize the utilization values for color mapping
  under_util = utilizations[utilizations < 100]
  if under_util.size > 0: # Ensure there are under-utilized values
    norm = mcolors.Normalize(vmin=np.min(under_util), vmax=100)
  else:
    norm = mcolors.Normalize(vmin=0, vmax=100) # Default normalization if no values are under 100
  util_cmap = plt.cm.summer # Distinct, soft colormap for under-utilization
  # Create grid values for width and thickness
  W, T = np.meshgrid(np.unique(widths), np.unique(thicknesses))
  weight_dict = {(width, thickness): weight for width, thickness, weight in zip(widths, thicknesses, weights)}
  W_flat, T_flat = W.flatten(), T.flatten()
```

```
Wt_flat = np.array([weight_dict.get((w, t), np.nan) for w, t in zip(W_flat, T_flat)])
Wt = Wt_flat.reshape(W.shape)
# Create the 3D plot
fig = plt.figure(figsize=(12, 8))
ax = fig.add_subplot(111, projection='3d')
surface = ax.plot_surface(W, T, Wt, cmap='Blues', edgecolor='none', alpha=0.5)
# Plotting individual points with selective gradient colors
for width, thickness, weight, utilization in zip(widths, thicknesses, weights, utilizations):
  if utilization >= 100:
    color = 'red' # Uniform color for over-utilization
    marker = 'x'
  else:
    color = util_cmap(norm(utilization)) # Gradient color for under-utilization
    marker = 'o'
  ax.scatter(width, thickness, weight, color=color, marker=marker, s=50)
# Labels and titles
ax.set_xlabel('Width (m)')
ax.set_ylabel('Thickness (m)')
ax.set_zlabel('Weight (kg)')
ax.set_title('3D Surface Plot of Weight vs Width and Thickness with Selective Gradient Utilization Markers')
```

Colorbar for the under-utilization values

```
sm_util = plt.cm.ScalarMappable(cmap=util_cmap, norm=norm)
sm_util.set_array([])
cbar_util = plt.colorbar(sm_util, ax=ax, aspect=10)
cbar_util.set_label('Utilization Value (%) (Under 100)')
# Colorbar for the surface weight values
sm_weight = plt.cm.ScalarMappable(cmap='Blues')
sm_weight.set_array(Wt)
cbar_weight = plt.colorbar(sm_weight, ax=ax, aspect=10)
cbar_weight.set_label('Weight (kg)')
plt.show()
# Pretty print the range of utilization values
min_util = np.min(utilizations)
max_util = np.max(utilizations)
print(f"Utilization Value Range: {min_util:.2f}% to {max_util:.2f}%")
def plot_results(results):
plt.figure(figsize=(10, 6))
```

Group results by width

```
grouped_results = {}
```

```
for result in results:
```

```
weight, width, thickness, length, util_bend, bend_status, util_shear, shear_status, util_sls, sls_status, util_cmprs, Compression_status, util_buckl_y, bkl_y_status, util_buckl_z, bkl_z_status, util_final, _ = result
```

```
if width not in grouped_results:
grouped_results[width] = []
```

```
grouped_results[width].append((thickness, weight, util_final))
```

```
# Create a colormap
width_values = sorted(grouped_results.keys())
colors = plt.cm.viridis(np.linspace(0, 1, len(width_values)))
width_to_color = dict(zip(width_values, colors))
```

Plot each group

for width, data in grouped_results.items():
 # Sort data by thickness for continuous lines
 data.sort()
 thicknesses, weights, utilizations = zip(*data)
 color = width_to_color[width]

Plot the line connecting the points
plt.plot(thicknesses, weights, linestyle='-', color=color, label=f'Width {width*1000:.0f} mm')

Plot individual points with different markers

for thickness, weight, utilization in zip(thicknesses, weights, utilizations): marker = 'o' if utilization < 100 else 'x' plt.scatter(thickness, weight, color=color, marker=marker)

```
plt.xlabel('Thickness (m)')
plt.ylabel('Weight (kg)')
plt.title('Weight vs. Thickness by Width and Utilisation')
plt.legend(title='Width', loc='upper left', bbox_to_anchor=(1.05, 1), borderaxespad=0.)
plt.grid(True)
plt.tight_layout()
plt.show()
def main():
```

y_m = 1.3 # Partial factor

User inputs for material properties and load

rho = 450 fm_k = 24 $fv_k = 4$ $fc_k = 30$ **E** = 11.3 $E_0_G_05 = 11.3$ $kmod_p = 0.5$ $kmod_m = 0.65$ kmod_i = 0.9 **P_L** = 2.96 **M_L** = 7.44 **L** = 5.66 **SLS_L** = 5.18 **gk** = 1.38 $g_lead = 2$ g_acmp = 1.4 K def = 2

```
psi_lead = 0
psi_acmp = 0.2
B_c = 0.2 #factor for solid timber
P_clm = 3.7
M_clm = 9.2
I_clm = 7
L = 2
L_clm = 2
n_width = 10
# widths = [float(input(f"Enter width {i+1} in mm: ")) / 1000 for i in range(n_width)]
widths = [75, 100, 115, 125, 138, 150, 175, 200, 225, 275, 300]
widths = [x / 1000 for x in widths]
n_thickness = 10
# thicknesses = [float(input(f"Enter thickness {i+1} in mm: ")) / 1000 for i in range(n_thickness)]
thicknesses = [35, 38, 44, 47, 50, 63, 75, 100, 150, 250, 300]
thicknesses = [x / 1000 for x in thicknesses]
# Derived design strength values
fm_d_p = (kmod_p * fm_k) / y_m
fm_d_m = (kmod_m * fm_k) / y_m
fm_d_i = (kmod_i * fm_k) / y_m
fv_d_p = (kmod_p * fv_k) / y_m
fv_d_m = (kmod_m * fv_k) / y_m
fv_d_i = (kmod_i * fv_k) / y_m
fc_d_p = (kmod_p * fc_k) / y_m
fc_d_m = (kmod_m * fc_k) / y_m
fc_d_i = (kmod_i * fc_k) / y_m
# Prepare to collect results
results = []
# Iteration over possible dimensions
for W in widths:
  for T in thicknesses:
    V = L * W * T
    Wt = rho * V
    I_y = (W * 1000) * ((T * 1000)**3) / 12 # Moment of inertia with correct units
    I_z = (T * 1000) * ((W * 1000)**3) / 12 # Moment of inertia with correct units
    # ULS Calculations for beam
    Md_1 = P_L * L * * 2 / 8
    Md_2 = M_L * L * 2 / 8
    Md_3 = I_k * L^{**2} / 8
    h = T \# Total depth of the beam
    # Shear and Bending stresses for ULS beam
    tau_1 = 3/2 * (P_L * L / 2) / (W * h) / 1000
    tau_2 = 3/2 * (M_L * L / 2) / (W * h) / 1000
    tau_3 = 3/2 * (I_L * L / 2) / (W * h) / 1000
    util_bend = max((Md_1 / I_y) * (h * 1000 / 2) * (10**6) / fm_d_p,
             (Md_2 / I_y) * (h * 1000 / 2) * (10**6) / fm_d_m,
             (Md_3 / l_y) * (h * 1000 / 2) * (10**6) / fm_d_i) * 100
    util_shear = max(tau_1 / fv_d_p, tau_2 / fv_d_m, tau_3 / fv_d_i) * 100
```

```
# SLS Calculations for deflection
      \delta_{inst} = 5*(1e6) * (SLS_L * L**4) / (384 * E * I_y)
      \delta_{crp_q} = 5*(1e6)*(qk*L**4)*K_{def}/(384*E*I_v)
      \delta_{crp_acmp} = 5*(1e6)*(g_{acmp}*L**4)*K_{def}*psi_{acmp}/(384*E*I_y)
       \delta_{\text{fin}} = \delta_{\text{inst}} + \delta_{\text{crp}} + \delta_{\text{crp}} + \delta_{\text{crp}}
      util_deflct_inst = \delta_{inst} / (L / 300) * 100
      util_deflct_fin = \delta_fin / (L / 150) * 100
      util_sls = max(util_deflct_inst, util_deflct_fin)
       # ULS Calculations for Column Compression
      Strs_c_1 = P_clm / ((W * T)*(1e3))
       Strs_c_2 = M_clm / ((W * T)*(1e3))
       Strs_c_3 = I_clm / ((W * T)*(1e3))
      util_cmprs = max(Strs_c_1 / fc_d_p, Strs_c_2 / fc_d_m, Strs_c_3 / fc_d_i) * 100
       # ULS Calculations for Column Buckling
      L_y = L_clm # Buckling lengths
      L_Z = L_clm
      i_y = (l_y / (W * T* (1e12)))**(1/2) #Radius of inertia
      i_z = (I_z / (W * T* (1e12)))**(1/2)
                              #Slenderness ratio
      sln_rtio_y = L_y/i_y
       sln_rtio_z = L_Z/i_z
      sln_rel_y = (((sln_rtio_y/mt.pi)) * (((fc_k/ E_0_G_05)*(10))**(1/2)))/100 #Relative slenderness ratio
      sln_rel_z = (((sln_rtio_z/ mt.pi)) * (((fc_k/ E_0_G_05)*(10))**(1/2)))/100
      k_y = 0.5 * (1 + B_c * (sln_rel_y - 0.3) + (sln_rel_y **2)) #Instability factor
      k_z = 0.5 * (1 + B_c * (sln_rel_z - 0.3) + (sln_rel_z **2))
      k_c_y = 1 / (k_y + mt.sqrt((k_y**2) - (sln_rel_y **2))) #Buckling reduction coefficient
      k_c_z = 1 / (k_z + mt.sqrt((k_z^{**2}) - (sln_rel_z^{**2})))
      util_buckl_y = (Strs_c_1/((k_c_y) * (fc_d_m))) * 100 #Utilization in plane
      util_buckl_z = (Strs_c_1/ ((k_c_z) * (fc_d_m))) * 100 #Utilization out of plane
       # Acceptability checks
      bend_status = "Acceptable" if util_bend < 100 else "Unacceptable"
       shear_status = "Acceptable" if util_shear < 100 else "Unacceptable"
       sls_status = "Acceptable" if util_sls < 100 else "Unacceptable"
       Compression_status = "Acceptable" if util_cmprs < 100 else "Unacceptable"
      bkl_y_status = "Acceptable" if util_buckl_y < 100 else "Unacceptable"
      bkl_z_status = "Acceptable" if util_buckl_z < 100 else "Unacceptable"
      util_final = max(util_bend,util_shear, util_sls, util_cmprs, util_buckl_y, util_buckl_z)
       final_status = "Acceptable" if util_final < 100 else "Unacceptable"
      results.append((Wt, W, T, L, util_bend, bend_status, util_shear, shear_status, util_sls, sls_status, util_cmprs,
Compression_status, util_buckl_y, bkl_y_status, util_buckl_z, bkl_z_status, util_final, final_status ))
  # Sort results by weight and print final summary
  results.sort() # Default sort by first element which is weight
  for result in results:
    print(f" Weight: {result[0]:.2f} kg, Width: {result[1]*1000:.0f} mm, "
       f"Thickness: {result[2]*1000:.0f} mm, Length: {result[3]:.2f} m, "
```

```
f"Bending Utilisation: {result[4]:.2f}%, Bending Status: {result[5]}, "
```

f"Shear Utilisation: {result[6]:.2f}%, Shear Status: {result[7]}, "
 f"SLS Utilisation: {result[8]:.2f}%, SLS Status: {result[9]}, "
 f"Compression Utilisation: {result[10]:.2f}%, Compression status: {result[11]}, "
 f"Buckling Utilisation in plane: {result[12]:.2f}%, Buckling status in plane: {result[13]}, "
 f"Buckling Utilisation out of plane: {result[14]:.2f}%, Buckling status out of plane: {result[15]}, "
 f"Final Utilisation: {result[16]:.2f}%, Final utilisation status: {result[17]}, ")
 plot_results(results)
 plot_3d_surface_with_distinct_gradient_markers(results)
 save_results_to_csv(results)
 if __name__ == "__main__":
 main()

Input script for load calculator

```
import math
# Functions from the first code
def calculate_kr(z0):
  z0_{II} = 0.05 # Fixed reference roughness length in meters
  return 0.19 * (z0 / z0_II)**0.07
def calculate_cr(kr, z, z0):
  return kr * math.log(z / z0)
def calculate_turbulence_intensity(k1, c0, z, z0):
  if z0 <= 0 or z <= z0:
    raise ValueError("z must be greater than z0 and z0 must be positive")
  return k1 / (c0 * math.log(z / z0))
def calculate_mean_wind_velocity(kr, c0, vb0, z, z0):
  cr = calculate_cr(kr, z, z0)
  return cr * c0 * vb0
def calculate_peak_wind_velocity_pressure(lv, rho, vm):
  qp = ((1 + 7 * Iv) * 0.5 * rho * vm ** 2)/1000
  return qp
def calculate_wind_pressure(qp, b, d, h):
  e = min(b, 2 * h)
  if e > 5 * d:
    A_width = d
    B_width = 0
    C_width = 0
  elif e > d:
    A_width = e / 5
    B_width = (d - e) / 5
    C_width = 0
  else:
    A_width = e / 5
    B_width = e * (4 / 5)
```

```
C_width = d - e
  h_d_ratio = h / d
  if h_d_ratio >= 5:
    cpe_values = {'A': -1.2, 'B': -0.8, 'C': -0.5, 'D': 0.8, 'E': -0.7}
  elif 1 <= h_d_ratio < 5:
    cpe_values = {'A': -1.2, 'B': -0.8, 'C': -0.5, 'D': 0.8, 'E': -0.5}
  elif 0.25 <= h_d_ratio < 1:
    cpe_values = {'A': -1.2, 'B': -0.8, 'C': -0.5, 'D': 0.7, 'E': -0.3}
  else:
    raise ValueError("h/d ratio out of range for defined cpe values")
  We_results = {}
  areas = ['A', 'B', 'C', 'D', 'E']
  for area in areas:
    We_results[area] = qp * cpe_values[area]
  return We_results, {'A_width': A_width, 'B_width': B_width, 'C_width': C_width}
def calculate_loads(We_direct, We_side, widths, h, d, n):
  max_pressures = {}
  areas = ['A', 'B', 'C', 'D', 'E']
  for area in areas:
    max_pressures[area] = max(We_direct[area], We_side[area])
  load_on_beam = (max(max_pressures.values()) * h) / 2
    max_pressures['A'] * widths['A_width'],
    max_pressures['B'] * widths['B_width'],
    max_pressures['C'] * widths['C_width'],
    max_pressures['D'] * d,
    max_pressures['E'] * d
  ) / (n / 2)
  return load_on_beam, load_on_column
def calculate_dead_load(rho, T_sl, W_sl, L_sl):
  volume = W_sl * L_sl * T_sl
  mass = volume * rho
  q = 9.81
  weight = mass * g
  dead_load_per_meter = (weight / L_sl) / 2 / 1000
  return dead_load_per_meter
def calculate_Live_load(W_sl, L_sl):
  Live_load = (1.5)* (W_sl * L_sl) # Assume a live load of 1.5 kN/m<sup>2</sup>
  qk = (Live_load / L_sl) / 2 / 1000
  return ak
def calculate_snow_load(W_sl,L_sl):
  M_i = 0.8 # Snow load shape coefficient
  Ce = 1.0 # Exposure coefficient
  Ct = 1.0 # Thermal coefficient
  s_g = float(input("Enter the Characteristic value of snow load (s.g): "))
  snow_load = ((M_i * Ce * Ct * s_g)*(W_sl * L_sl))
```

```
sk= ((snow_load)/ L_sl)/2/1000
  return sk
def Beam_load_combinations():
  # Constants
  y_g = 1.35
  y_q = 1.5
  \Psi_0_q = 0
  \Psi_0_w = 0.6
  altitude = float(input("Enter the altitude of the site: "))
  if altitude > 1000:
   height = 2
  else:
    height = 1
  if height == 1:
    \Psi_0_s = 0.7
  else:
    \Psi_0_s = 0.5
  # Inputs for dead load calculation
  rho = float(input("Enter the density of the slab material (kg/m<sup>3</sup>): "))
  T_sl = float(input("Enter the thickness of the slab (m): "))
  W_sl = float(input("Enter the width of the slab (m): "))
  L_sl = float(input("Enter the length of the slab (m): "))
  gk = calculate_dead_load(rho, T_sl, W_sl, L_sl)
  print(f"The calculated dead load on the beam (gk) is {gk:.2f} kN/m")
  gk = calculate_Live_load(W_sl, L_sl)
  sk= calculate_snow_load(W_sl,L_sl)
  # Get the wind load inputs
  h = float(input("Enter the height of the building h (m): "))
           #input("Enter the height at which the wind speed is considered (z) in (m)
  z = h
  z0 = float(input("Enter the roughness length (z0) in meters: "))
  c0 = float(input("Enter the orography factor (c0): "))
  vb0 = float(input("Enter the basic wind speed (vb0) in m/s: "))
  b = W_sl #input("Enter the width of the building b (m)
  d = L_s l #input("Enter the length of the building d (m)
  n = int(input("Enter the number of columns n: "))
  # Calculating kr, lv, Vm, and qp using the first code's functions
  kr = calculate_kr(z0)
  Iv = calculate_turbulence_intensity(1, c0, z, z0)
  vm = calculate_mean_wind_velocity(kr, c0, vb0, z, z0)
  qp = calculate_peak_wind_velocity_pressure(lv, 1.25, vm) # rho is 1.25 kg/m^3
  print(f"Calculated peak velocity pressure qp: {qp:.2f} Pa\n")
  # Calculate for direct wind
  We_direct, widths_direct = calculate_wind_pressure(qp, b, d, h)
  print_results(We_direct, "direct")
  # Calculate for side wind (just swapping b and d)
  We_side, widths_side = calculate_wind_pressure(qp, d, b, h)
  print_results(We_side, "side")
```

```
# Calculate wind loads
```

```
wk, load_on_column = calculate_loads(We_direct, We_side, widths_direct, h, d, n)
print(f"Wind load on the beam (wk): {wk:.2f} kN/m")
print(f"Load on the column: {load_on_column:.2f} kN")
ULS_category1 = [\gamma_g * gk]
  (\gamma_g * gk) + (\gamma_q * qk),
  (\gamma_{g} * gk) + (\gamma_{q} * qk) + (\Psi_{0_{s}} * \gamma_{q} * sk),
  (\gamma_{q} * gk) + (\gamma_{q} * qk) + (\Psi_{0} w * \gamma_{q} * wk)
ULS_category3 = [
  (\gamma_{q} * gk) + (\gamma_{q} * qk) + (\Psi_{0} * \gamma_{q} * sk) + (\Psi_{0} * \gamma_{q} * wk),
  (\gamma_{q} * gk) + (\Psi_{0} + \gamma_{q} * qk) + (\gamma_{q} * sk) + (\Psi_{0} + \gamma_{q} * wk),
  (\gamma_{g} * gk) + (\Psi_{0_{q}} * \gamma_{q} * qk) + (\Psi_{0_{s}} * \gamma_{q} * sk) + (\gamma_{q} * wk),
  (\gamma_g * gk) + (\gamma_q * sk),
  (\gamma_{g} * gk) + (\gamma_{q} * wk),
  (\gamma_{g} * gk) + (\gamma_{q} * sk) + (\Psi_{0} w * \gamma_{q} * wk),
  (\gamma_{g} * gk) + (\gamma_{q} * wk) + (\Psi_{0_{s}} * \gamma_{q} * sk),
  (\gamma_{q} * gk) + (\Psi_{0}q * \gamma_{q} * qk) + (\gamma_{q} * sk),
  (\gamma_{g} * gk) + (\Psi_{0}q * \gamma_{q} * qk) + (\gamma_{q} * wk)
max_category1 = max(ULS_category1)
max_category2 = max(ULS_category2)
max_category3 = max(ULS_category3)
  gk,
  qk + qk,
  gk + qk + \Psi_0_s * sk,
  gk + qk + \Psi_0 w * wk,
  gk + qk + \Psi_0_s * sk + \Psi_0_w * wk,
  qk + \Psi_0_q * qk + sk + \Psi_0_w * wk,
  gk + \Psi_0_q * qk + \Psi_0_s * sk + wk,
  gk + sk,
  gk + wk,
  qk + sk + \Psi_0 w * wk
  gk + wk + \Psi_0_s * sk,
  gk + \Psi_0_q * qk + sk,
  gk + \Psi_0_q * qk + wk
max_SLS = max(SLS_combinations)
Lead_varbl = max(qk, sk, wk)
if Lead_varbl == qk:
  psi_lead = 0
elif Lead_varbl == sk:
  if height == 1:
```

```
psi_lead = 0.2
    else:
      psi_lead = 0.5
  elif Lead_varbl == wk:
    psi_lead = 0.2
  values = [qk, sk, wk]
  values.remove(Lead_varbl)
  acmp_varbl = max(values)
  if acmp_varbl == qk:
    psi_acmp = 0
  elif acmp_varbl == sk:
    if height == 1:
      psi_acmp = 0
    else:
      psi_acmp = 0.2
  elif acmp_varbl == wk:
    psi_acmp = 0
  print(f"Maximum load for ULS Category 1 (Permanent): {max_category1:.2f} kN/m")
  print(f"Maximum load for ULS Category 2 (Medium-term): {max_category2:.2f} kN/m")
  print(f"Maximum load for ULS Category 3 (Instantaneous): {max_category3:.2f} kN/m")
  print(f"Maximum load for SLS: {max_SLS:.2f} kN/m")
  print(f"Leading varible action: {Lead_varbl:.2f} kN/m")
  print(f"accompanying variable action: {acmp_varbl:.2f} kN/m")
  print(f"psi_lead: {psi_lead:.2f}")
  print(f"psi_acmp: {psi_acmp:.2f}")
def print_results(We_results, wind_direction):
  print(f"Wind pressure results for {wind_direction} wind:")
  for area, pressure in We_results.items():
    print(f"We for area {area}: {pressure:.2f} Pa")
  print("\n")
# Call the function to run the combined code
```

Beam_load_combinations()

Input script for G-code Genrator

```
def generate_gcode(
  mortise_width,
  mortise_height,
  mortise_depth,
  tenon_width,
  tenon_height,
  tenon_length,
  peg_diameter,
  peg_depth,
  num_pegs,
  tool_diameter,
  feed_rate,
  spindle_speed,
  safe_z,
  step_down=2, # Added step-down parameter
  """Generates G-code for a pegged mortise and tenon joint."""
```

gcode = ""

):

Setup

gcode += "G21\n" # Set units to millimeters

gcode += "G17\n" # Set XY plane

gcode += "G90\n" # Set to absolute coordinates

gcode += f"F{feed_rate}\n"

gcode += f"S{spindle_speed}\n"

Mortise

```
gcode += mill_pocket(
```

0, 0, -mortise_depth, mortise_width, mortise_height, tool_diameter, safe_z, step_down

)

Tenon

```
gcode += mill_pocket(
```

0,

0,

-tenon_length,

tenon_width,

tenon_height,

tool_diameter,

safe_z,

step_down,

)

```
# Peg holes
```

peg_spacing = mortise_width / (num_pegs + 1)

for i in range(num_pegs):

```
x_pos = peg_spacing * (i + 1)
```

gcode += drill_hole(x_pos, mortise_height / 2, -peg_depth, peg_diameter, safe_z)

End of program

gcode += "M30\n"

return gcode

def mill_pocket(x_start, y_start, z_depth, width, height, tool_diameter, safe_z, step_down):

""Generates G-code to mill a pocket."""

gcode = ""

current_z = 0

while current_z > z_depth:

current_z -= step_down

gcode += f"G0 Z{safe_z}\n"

gcode += f"G0 X{x_start + tool_diameter/2} Y{y_start + tool_diameter/2}\n"

gcode += f"G1 Z{current_z}\n"

gcode += f"G1 X{x_start + width - tool_diameter/2}\n"

gcode += f"G1 Y{y_start + height - tool_diameter/2}\n"

gcode += f"G1 X{x_start + tool_diameter/2}\n"

gcode += f"G1 Y{y_start + tool_diameter/2}\n"

gcode += f"G0 Z{safe_z}\n"

return gcode

def drill_hole(x_pos, y_pos, z_depth, diameter, safe_z):

""Generates G-code to drill a hole."""

gcode = ""

gcode += f"G0 Z{safe_z}\n"

gcode += f"G0 X{x_pos} Y{y_pos}\n"

gcode += f"G1 Z{z_depth}\n" # Use a drilling cycle (e.g., G81) if supported

gcode += f"G0 Z{safe_z}\n"

return gcode

```
# Example usage
```

gcode_program = generate_gcode(

mortise_width=20,

mortise_height=40,

mortise_depth=10,

tenon_width=18,

tenon_height=38,

tenon_length=15,

peg_diameter=6,

peg_depth=20,

num_pegs=2,

tool_diameter=8,

feed_rate=1000,

spindle_speed=10000,

safe_z=10,

) print(gcode_program)

Appendix F: Input script for Joint Optimiser

```
import math
import matplotlib.pyplot as plt
import numpy as np
# Calculate the capcity of peg and spacing requierments
def calculate_capacity_and_status_for_graph(
  w_clmn, b_clmn, w_t, tau_c, F_ed, F_em, F_es,
  required_load_kN, Ke, Re, k3, dtl_e, dtl_s, dtl_v, dtl_g,
  n, tm, ts ):
  D_values = []
  capacity_values = []
  # Iterate over D values, converting floats to ints
  for D in range(int(0.5 \times 100), int((b_clmn/4) \times 100) + 1, int(0.01 \times 100)):
    D = D / 100 \# Convert back to float for calculations
    # 1. Calculate Capacity Components
    PId = (n * D * tm * F_ed) / 2
    PIm = (n * D * tm * F_em) / 2
    Pls = n * D * ts * F_es
    PVd = (n * math.pi * (D ** 2) * tau_c) / 4
    # 2. Find Overall Capacity
    capacity = min(Pld, Plm, Pls, PVd)
    # 3. Check if the Joint is Strong Enough
    status = "Acceptable" if (
       capacity >= required_load and
       lim_v + lim_e < b_clmn and
       (2 \times \lim_{g}) + \lim_{g} < w_t
    ) else "Not Acceptable"
    # 4. Calculate Equivalent Steel Diameter Bolt
    Z = capacity
    d_im = (4 * Ke * Z) / (tm * F_em)
    d_i = (2 * Ke * Z) / (ts * F_e)
    d_{iiis} = (1.6 * Ke * Z * (2 + Re)) / (k3 * ts * F_em)
    d_iv = (math.sqrt((1.6 * Ke * Z * math.sqrt(3 * (1 + Re))) / math.sqrt(2 * F_em * F_es))) / 2
    d_eq = max(d_im, d_is, d_iiis, d_iv)
    # 5. Calculate Limits for Placement of the Dowel
    \lim_e = dtl_e * d_eq
    lim_s = dtl_s * d_eq
    \lim_v = dtl_v * d_eq
    \lim_g = dtl_g * d_eq
    # 6. Check if Dowel Placement is OK
    limit_check_v_e = lim_v + lim_e < b_clmn
    limit_check_g_s = (2 * lim_g) + lim_s < w_t
    # 7. Print the Results in the desired format
    D_mm = D * 25.4
```

```
lim_e_mm = lim_e * 25.4
lim_s_mm = lim_s * 25.4
lim_v_mm = lim_v * 25.4
lim_g_mm = lim_g * 25.4
capacity_kN = capacity * 0.00444822
```

print(f"{D_mm:.3f}, {lim_e_mm:.2f}, {lim_s_mm:.2f}, {lim_v_mm:.2f}, {lim_g_mm:.2f}, {capacity_kN:.2f}, {status} ")

```
# Collect values for plotting
    capacity_values.append(capacity_kN)
    statuses.append(status)
  return D_values, capacity_values, statuses
# Input parameters (we are iterating over it D)
w_clmn = 3.93701 #100 mm
b_clmn = 4.4291339 #112.5 mm
w_t = 6 #152.4 mm
tau_c = 1518
F_ed = 2688
F_em = 5488
F_es = 2660
required_load = 1000
Ke = 0.625
Re = 2.063
k3 = 1.3
dtl_e = 2
dtl_s = 2.5
dtl_v = 1.5
dtl_g = 1.5
n = 2
tm = (w_clmn/3)
ts = tm
required_load_kN= required_load * 0.00444822
# Get the values for plotting
D_values, capacity_values, statuses = calculate_capacity_and_status_for_graph(
  w_clmn, b_clmn, w_t, tau_c, F_ed, F_em, F_es,
  required_load_kN, Ke, Re, k3, dtl_e, dtl_s, dtl_v, dtl_g,
  n, tm, ts,
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