CHALMERS
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Intelligent Roof Truss Digitalization of the building Process

Master’s thesis in Structural Engineering and Building Technology

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CHALMERS UNIVERSITY OF TECHNOLOGY
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MASTER'S THESIS 2023

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Lightweight Structures
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Master's Thesis 2023
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ABSTRACT

Sweden has a big market for different wood and timber products, but the raw material usage still can be improved and optimized to its full strength and potential. The modern building and construction industry uses wood according to its specified property values in the different strength classes. However, it is well known that wood has a considerable natural variability in its properties. In the grading process, the fifth percentile value, also called the characteristic value, is used to declare and specify the properties in the respective class of the structural wood member. This means that in a batch of wood members from a strength class, 95% of all the members have a strength value above the specified characteristic value. This aspect and uncertainty of the actual strength of an individual timber member is considered in the calibration of safety factors in the design standards, which aim at a certain target reliability. In this thesis the potential of using the knowledge of the updated and actual material properties of the individual wood members in the design and assembly process of structures in order to increase safety and enhance resource efficiency is studied. So far truss builders don't use the results and knowledge from the grading process they determined for each single piece of wood. Instead, they only use the characteristic values from the strength class. Instead, in the design and assembly process of structures, the members can be allocated in the structure according to their actual properties, which can be used to increase the safety. In places with more demands in terms of strength the wood members with the highest actual strength values can be used, and in places with lower demands wood with lower actual strength is used. In this thesis, this process is simulated in models in the software MATLAB and RFEM and the probability of failure is determined. The results show that the probability of failure can be reduced by using the updated knowledge of the individual property values of each wood member instead of the characteristic value only. The raw material saving potential for a more recourse efficient construction is evaluated.

Key words: Fink timber truss, grading of timber, characteristics value, structural reliability, probability of failure

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1 Introduction

1.1 Background

Due to the cutting processes, the different growth conditions as well as because of the non-homogeneous structure of the material, timber has variable properties (Fink, 2014).Nonetheless, timber is reliably used for different structural and non-structural purposes. Hardwoods are usually used in cladding and exposed works where strength and aesthetics like colour and pattern are required. On the other hand, softwoods are often used for efficient and economic timber structures). (Victor, 2020).Particularly in buildings, timber is used as a major structural component for different purposes such as the floor, ceiling, walls, and roof trusses. The timber is used as structural timber alone or as prefabricated building components such as glulam beams. This master thesis focuses on the roof truss structural component of the timber structure. Roof trusses are frameworks that are used to support the roof of a building and have both an aesthetic and structural purpose in the building.

The strength of timber normally is influenced from how the tree grows and the natural characteristics of the tree. Due to the natural variability of the wood material and in order to achieve a reliable building product under European standards, timber is either visually graded or machine-graded (Ridley-Ellis et al., 2016).The visual grading system is usually done through grading rules on national basis such as SS 230120. Although the simplicity and fewer technical requirements make the visual grading system easier to apply by simple means, it is not a powerful predictor for grade determining properties such as timber strength and stiffness (Ridley-Ellis et al., 2016). On the contrary, the machine or mechanical grading system is done with predetermined settings or machine control and continuous verification (test and control) of the output. Machine grading is a more powerful predictor than visual grading as the machine can measure non-destructively properties of the timber to determine or indicate the grade-determining properties (Ridley-Ellis et al., 2016). Timber elements for trusses are machine graded to several strength classes which these classes are then used for the design and layout of the truss geometry. However, the choice of the cross-section of members is adjusted manually and verified afterward if it achieves the required load-bearing capacity (strength), deflection, and stability.

The method of grading timber into classes and using the properties of these classes in design nonetheless requires a relatively high safety margin in design and production. Still timber structures are exposed to collapse and failure which may occur due to the placement of weak members from a class in unfavourable positions.

1.2 Aim and Objectives

The thesis aims to evaluate the impact of the actual element properties using digital twins of structures under the performance of the structure and assess the possibilities of further optimization in parametric processes. Updated information on timber elements will be used in the design and validation process by taking the actual material properties into consideration rather than only the 5% characteristic property values and associated safety factor.

1.3 Methodology

To bring the thesis to a successful conclusion, there are several measures that must be performed.

1. The procedure of grading timber should be made clear to the reader after conducting research on relevant material, as this is the major goal of the study. The thought process that goes into assigning grades to timber.
2. The construction process of roof trusses, in particular the ways in which architects and engineers can take advantage of the inherent qualities of timber, will also be investigated as part of this study. Among the types of references that were consulted for this thesis are books, scholarly journals, and papers presented at conferences that focused on the topic of wood grading and roof trusses.
3. Following that, data on wood grading will be collected so that a numerical model of a roof truss can be built. The collected material model for timber will then be used to construct a parametric model of the structures.
4. This will be followed by an assessment of the conventional safety level with "intelligent" trusses, and finally, the model will be used to optimize the performance, safety, and material consumption of the structures. The software MATLAB as well as RFEM will be used to model the parametric model and analyse the data.

1.4 Limitations

There are several types of timber trusses, and this master thesis focuses on fink trusses. Fink truss is a wider used and highly efficient design featuring a W-shape various diagonal members that extend at different angles from the top of the end post to meet the bottoms of the vertical members. It is lightweight, easy to manufacture, and suitable for various roof spans. This truss type illustrates a truss that has been designed in accordance with the grading data of structural timber which represent various strength properties.

Other limitations such as:

- Design of supports, joints and connections do not fall under the scope of this thesis, however the joint should follow basic guidelines. As example, the centrelines of members connecting at a node should meet at the same point in the node during RFEM.
- The project studied only individual truss members and it did not consider columns bearing the truss roof.
- The selection of the appropriate structural selection for roof truss depends on factors such as the span, the loading requirements, the design criteria, and the available materials (strength, stiffness, assembly, etc.)

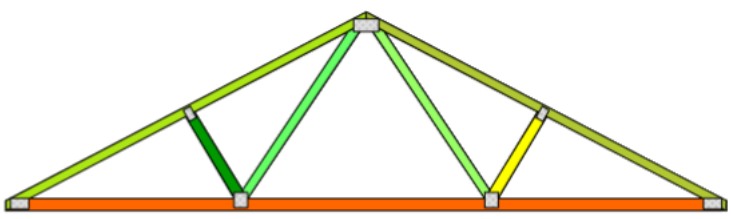

Figure 1.1 The Fink truss, or W-truss ,will be created in this thesis (Jockwer, R., 2020)

2 Literature Review

The following is an overview of the necessary background knowledge to proceed with the study. Some of the topics covered are the basics of wood as a material, the various timber connections available, loads on the roof and structural reliability are among the subjected discuss.

2.1 Timber as Construction Material

Wood is a traditional construction material that has been utilized for eons. It is a naturally occurring organic substance with multiple advantages. It can be manufactured in a multitude of shapes and sizes and has a high strength-to-weight ratio. It can be combined with other building materials and is truly renewable material.

Since wood is a natural biological material, its application is fraught with complications. Its characteristics are highly variable and responsive to climatic and loading conditions. It is orthotropic due to its high strength and rigidity parallel to the grain, i.e., in the longitudinal direction (L), but its deficient strength qualities perpendicular to the grain (P), i.e., in the radial and tangential directions (R, T). In addition to having varying strength and rigidity, the material also exhibits varying shrinkage/swelling properties in all three orthogonal orientations. Figure 2.1 illustrates orthoptic directions (Harte, 2009)

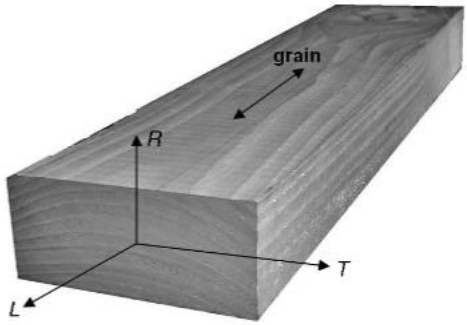

Figure 2.1 Orthotropic direction for wood(Harte, 2009)

Wood is a hygroscopic material capable of exchanging moisture with its surrounding environment. The moisture content of wood, which is defined as the ratio of the mass of water that can be extracted from the wood to the mass of dried wood, has a substantial effect on the wood's properties. Not only due to variations in strength and swelling/shrinking, but also because wood is susceptible to attack by a variety of organisms, the moisture level must be meticulously determined. If the moisture level in an exposed environment cannot be controlled, a preservative treatment may be used.

Mechanical characteristics are typically measured on timber specimens having a moisture level of around 12%. Mechanical characteristics are derived through testing and grading, in which the material is classified to satisfy numerous end-user criteria and guarantee product dependability. When designing structural components, one must consider the possibility of defects. Defects like tangles make it difficult to determine

the material's true strength. It is analytically defined by presuming defects are dispersed throughout the volume and thus dependent on the element size (Harte, 2009)

2.1.1 Engineering wood Products

The cross section and length of sawn timber are constrained by the dimensions of the log and the manufacturing process. According to SvenskaTra, the utmost depth and length are 245mm and 5.5m, respectively. To accomplish larger dimensions, engineered wood products (EWP) can be manufactured from sawn timber boards, veneers, fibres, or particle boards that have been bonded together with adhesives. Most of these EWPs, including beams and panels, were created in North America during the 20th century. Figure 2.2 depicts a chronology of the development of several of the EWPs. Small-diameter trees and low-grade timbers can be used to create a product with acceptable structural qualities due to the combination of the various elements. This is essential from both an economic and environmental standpoint (Swedish Wood, 2015)

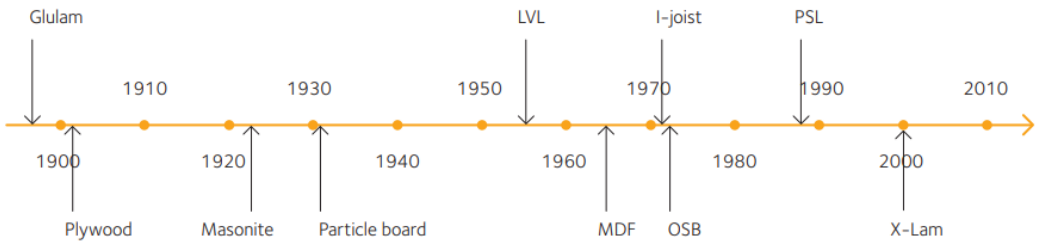

Figure 2.2 Development of EWP over the 20th century (Swedish Wood, 2015).

The probability density function of sawn wood versus glulam strength is depicted in Figure 2.3. Sawn timber's strength is reduced by cross-sectional imperfections such as branches. EWP, on the other hand, is more easily managed for quality, and the combination of wider portions (Weibull effect) increases strength while decreasing dispersion in comparison to sawn wood(TräGuiden, 2017)

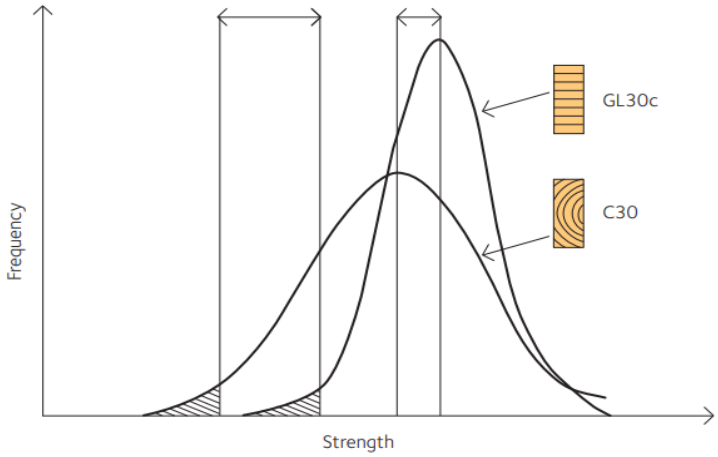

Figure 2.3 Probability curve of swan timber C30 and EWP (GL30c) (Swedish Wood, 2015)

2.2 Strength property of timber

European standards categorize timber used for structural purposes into classes and classifications of strength. A strength class is a strength grade where the timber has been assigned physical and mechanical properties for use in structural design computations.

(Hansson & Thelandersson, 2003) When grading the strength of wood, it is regarded as a homogeneous material with consistent strength throughout the entire specimen. The strength of the wood is referred to as its characteristic value, also known as the 5th percentile, which indicates that 95% of all specimens possess greater strength than the assigned grade. This could result in excessively large safety margins for wood structures (Hansson & Thelandersson, 2003).The strength of timber follows a log-normal cumulative distribution, which is represented in the below Figure 2.4.

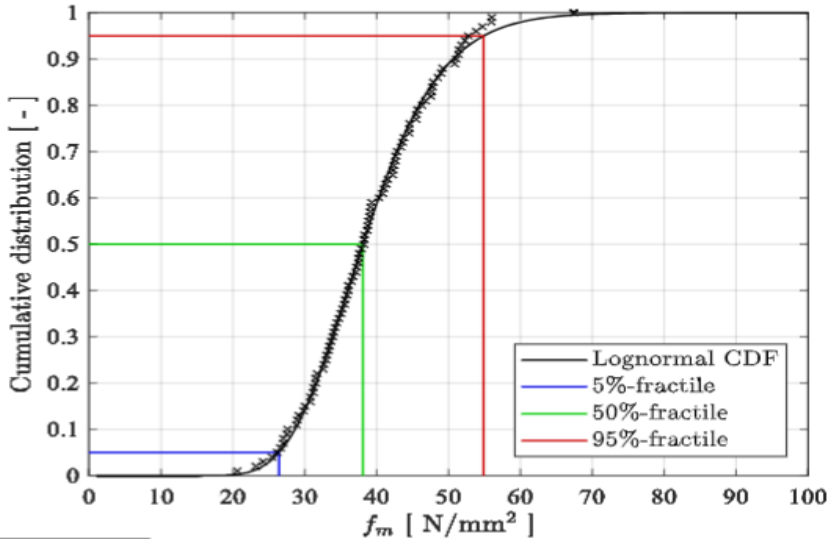

Figure 2.4 Log-normal cumulative distribution of simulated strength properties of timber (Jockwer, R., 2020)

In Europe, three essential characteristics are considered when evaluating timber samples: strength, rigidity, and density. Using two European standards, EN408 and EN384, along with a reference moisture content of 65 percent and a temperature of 20 degrees Celsius.

Sawing timbers results in the production of enormous structural elements (Swedish Wood, 2016a). After undergoing a series of procedures, the wood is available for use in construction. According to Table 2.1, solid wood is categorized from C14 to D70 based on its bending strength $f_{m,k}$ in MPa. The letter identifies the timber as either softwood or hardwood.

Table 2.1 Strength class -Characteristics value according to EN338.

		Coniferous species and Poplar												Deciduous species					
		C14	C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50	D30	D35	D40	D50	D60	D70
Strength properties in N/mm^2																			
Bending	$f_{m,k}$	14	16	18	20	22	24	27	30	35	40	45	50	30	35	40	50	60	70
Tension parallel to grain	$f_{t,0,k}$	8	10	11	12	13	14	16	18	21	24	27	30	18	21	24	30	36	42
Tension perpendicular to grain	$f_{t,90,k}$	0,4	0,5	0,5	0,5	0,5	0,5	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6
Compression parallel to grain	$f_{c,0,k}$	16	17	18	19	20	21	22	23	25	26	27	29	23	25	26	29	32	34
Compression perpendicular to grain	$f_{c,90,k}$	2,0	2,2	2,2	2,3	2,4	2,5	2,6	2,7	2,8	2,9	3,1	3,2	8,0	8,4	8,8	9,7	10,5	13,5
Shear	$f_{v,k}$	1,7	1,8	2,0	2,2	2,4	2,5	2,8	3,0	3,4	3,8	3,8	3,8	3,0	3,4	3,8	4,6	5,3	6,0
Stiffness properties in kN/mm^2																			
Mean value of modulus of elasticity parallel to grain	$E_{0,mean}$	7	8	9	9,5	10	11	11,5	12	13	14	15	16	10	10	11	14	17	20
5% value of modulus of elasticity parallel to grain	$E_{0,05}$	4,7	5,4	6,0	6,4	6,7	7,4	7,7	8,0	8,7	9,4	10,0	10,7	8,0	8,7	9,4	11,8	14,3	16,8
Mean value of modulus of elasticity pependicular to grain	$E_{90,mean}$	0,23	0,27	0,30	0,32	0,33	0,37	0,38	0,40	0,43	0,47	0,50	0,53	0,64	0,69	0,75	0,93	1,13	1,33
Mean value of shear modulus	G_{mean}	0,44	0,5	0,56	0,59	0,63	0,69	0,72	0,75	0,81	0,88	0,94	1,00	0,60	0,65	0,70	0,88	1,06	1,25
Density in kg/m^3																			
Density	ρ_k	290	310	320	330	340	350	370	380	400	420	440	460	530	560	590	650	700	900
Mean value of density	ρ_{mean}	350	370	380	390	410	420	450	460	480	500	520	550	640	670	700	780	840	1080

2.3 System of Grading Timber

There are two distinct approaches of grading wood. Evaluations are both visually and mechanically based. The mechanical or machine grading process is a laborious process in which the wood must fulfil and pass through specific requirements to be issued distinguishing grade stamps such as grade, producer, identification number, and condition. These stamps may be found on the wood. This kind of grading is more sophisticated than visual grading, and it provides a safer and more reliable estimate of the strength of the material. The most frequent approach to grading timber in Europe is achieved using machines. To categorize the timber, a machine takes readings on one or more of the wood's properties. On the other hand, visual grading entails visually assessing structural timber and supplying certain visual qualities for evaluation in accordance with recognized national criteria. During this grading procedure, physical anomalies such as knots, ring width, grain slope, and wane are measured to calculate the highest value that may be assigned to a specific grade for each of these traits. Several authors (Fortuna et al., 2018)

2.3.1 Visual Strength Grading

Visual grading, which should not the same as appearance grading. It has been around for centuries and is still utilized in a variety of contexts today. Throughout the grading process, the look of the wood is a factor that is taken into consideration.

The standards that are outlined in the European standard EN18081-1 need to be adhered to when performing the visual grading of timber. Even though there are standards that are recognized on a global scale, it is possible for each country to employ a relatively unique set of standards for grading a person's visual acuity. The laws in each country have been adapted to account for the species of wood that are most frequently found in that region.

Every piece of wood is visually evaluated and given a grade based on the properties that contribute to its total strength. These qualities are reaction wood, stiffness, density, grain slope, and ring width. The ultimate grade assigned to the specimen will be determined by how well it satisfies all these aesthetic criteria.

The visual characteristics of timber are not always the best predictor of the timber properties, and visual strength grading may not be the best approach to assess the real properties of timber when taking into mind the safety margin to allow for human error. In addition, the properties of timber can be misjudged based on the appearance of the timber. However, because visual strength grading needs fewer resources, it is a good starting point for guaranteeing that a larger diversity of species may be used in construction projects (Ridley-Ellis et al., 2016).This is possible because visual strength grading is a more cost-effective method.

One of the most fundamental limitations of visual grading is that it cannot adjust for any distortions of the timber that are not apparent on the surface. This is one of the reasons why visual grading is not as accurate as other methods. The inherent uncertainty of the visual grading approach results in a wider safety margin than that of the machine grading method (Ridley-Ellis et al., 2016) This is because the visual grading method is used.

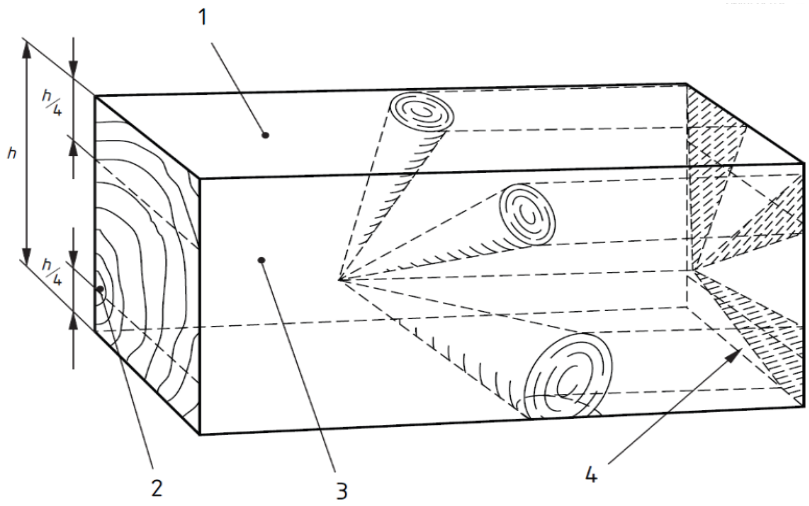

Figure 2.5 Visual grading (Ridley-Ellis, 2016)

2.3.1.1 Knots in Sawn timber

Sawn timber can contain a variety of knots, each of which has its own set of specifications for what constitutes an acceptable grade. Knot illustrations are shown in Figure 2.6.

- Traversing edge Knots
- Traversing arris knots
- Round or oval knots
- Spike knots
- Pin knots
- Splay knots

Figure 2.6 Different shapes of knots (Swedish Wood, 2016b)

The EN 338 European Standard Groups of specimens or pieces of the same species and source with comparable strength qualities are referred to as strength grades or strength classes in structural wood. The strength (MOR), density (ρ), and modulus of elasticity (MOE) are the three grade-determining parameters that characterize strength qualities. To designate specimens to a particular strength grade, the three grade determining properties' (GDP) characteristic values—a mean value for MOE and a fifth percentile value for MOR and (ρ)must match the prescribed values. Strength grades are established for both softwood (C-grades) and hardwood (D-grades) bending strength tests, as well as tension strength classes for softwood (T-grades). Classes are made to suit the property profiles of most common species as closely as possible.

While the shared Nordic designation is INSTA 142, they are issued under the Swedish standard SS 230120 in Sweden. Sitka spruce, Douglas fir, larch, pine, and silver spruce are all covered by the regulations. There are three classes: T0, T1, T2, and T3. The wood is still referred to as T-virke.

For the visual strength grading of timber, the classes T0, T1, T2, and T3 are used this class can be assigned to C-classes as shown in the table below.

Table 2.2 Grading of construction timber (Swedish Wood, 2016b)

Strength class	C14	C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50
Visual grading in line with SS 230120	T0		T1			T2		T3				
Mechanical grading in line with SS-EN 338		C16	C18	C20	C22	C24	C27	C30	C35	C40	C45	C50

The strength classes marked in orange are the manufacturing standard for Swedish manufacturers of strength grade construction timber.

Figure 2.7 shows a standard link between knot ratio and bending strength for soft woods. One common measure of knot significance is the knot ratio. You may easily visualize this by dividing the knot's diameter at the cross section by the beam's depth. In most cases, the largest size of the cross section is the depth, which is the dimension of the beam in the loading direction. This is an example of edgewise bending, which is often referred to as "using the biggest dimension as depth."

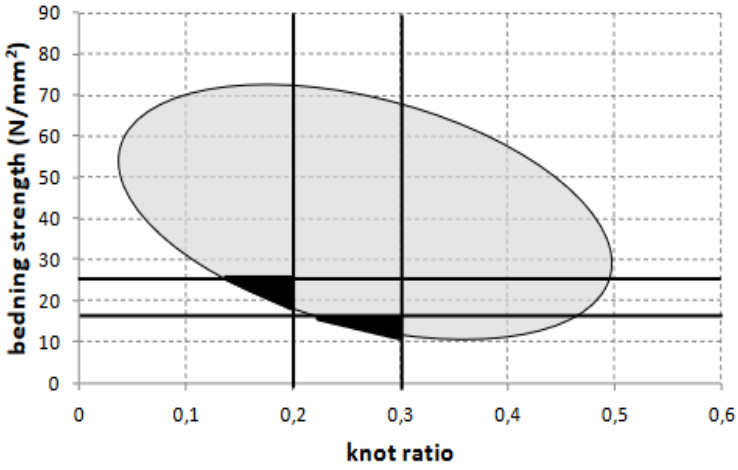

Figure 2.7 Bending strength against the knotting ratio for softwood and hardwood (Ravenshorst, 2015).

Figure 2.7 illustrates how the magnitude range across which the characteristics appear impacts the number of grades and the variety of strength class allocations for each grade. A check using a knot ratio between zero and sixty-three percent. A curve representing the knot ratio bending strength data points for each specimen is displayed in the plots. In the higher grade, the knot ratio is between 0 and 0.2, whereas in the lower grade, it is between 0.2 and 0.3. Pieces with a knot ratio greater than 0.3 are considered unacceptable since they cannot be reinforced in any way. For each grade, the depth locations with the lowest bending strength values at 5% are denoted by a black triangle. Above these triangles, where the vertical axis meets the horizontal line, is where the gradient is broken down into its component parts at the rate of five percent. There needs to be a significant separation between the 5% fractals of the grades for the grading to be helpful. In this scenario, there is just one visible quality level that can be identified.

2.3.2 Machine Strength Grading

Machine grading of timber, also known as mechanical grading, may be broken down into two distinct approaches: machine controlled, and output controlled. The output is managed by continuous testing, while the machine is controlled depending on the settings that were previously specified for the machine.

In a manner analogous to that of the visual strength grading, the machine conducts non-destructive testing on each specimen. During a visual strength grading, there are certain qualities that can be measured, and it is considered that these properties are a better predictor of strength than the properties that may be measured otherwise. It is possible for machine grading to be completed quicker than visual grading and, in most cases, with a higher level of accuracy. This is made possible by the presence of x-rays in the machines, which can identify knots that are not apparent on the surface, and there is also a lower likelihood of mistakes being made by humans (Ridley-Ellis et al., 2016)

According to (Deublein et al., 2010) machine grading is a viable choice since current production of structural timber needs to be carried out in a quick, reliable, and cost-effective manner.

There are some lists of marking tools, like

- ✓ Bending stiffness
  - Bending about the minor axis.
- ✓ Dynamic (acoustic/vibration)
  - Essentially a measure of stiffness.
  - May or may not include density.
- ✓ X-rays
  - A combination of knots and density.
  - Perhaps with optical camera.
- ✓ Assessment of slope of grain and so on

2.3.2.1 Machine Control Grading

The machine control grading systems depend on specified parameters that were derived from an earlier destructive test that was carried out. The settings that are utilized are variable depending on the species being worked with, as well as the origin of the timber. If the provenance of the timber is different, then the machine control parameters must be adjusted accordingly (Ridley-Ellis et al., 2016). This is true even if the species being worked on are same.

2.3.2.2 Output Control Grading

To make use of this technology, the manufacturer must routinely evaluate the results of their work and make necessary adjustments to the machine's parameters. Since this approach isn't utilized very frequently, the processes that are outlined in the European Standard EN14081-1 aren't very well established (Ridley-Ellis et al., 2016)

3 Roof Trusses

This chapter will provide a quick review of trusses, including the many types of trusses as well as the principal truss that will be examined in this thesis. The design process will be discussed in greater depth.

Trusses are triangular frame structures made up of axially loaded elements. Because the cross section of all the components is nearly evenly strained, they are more efficient in resisting external stresses. The members of a truss respond only in axial compression or tension, making it an assembly rather than a single component. In a truss, the chords are the top and bottom members, and the web members are the middle ones. Members of a web that are under tension are termed ties, and members that are under compression are called struts. In a perfect truss, the points where the members connect are called joints or nodes, and these nodes are idealized as hinges or pins that cannot convey bending force. While loads are only applied at the nodes and joints of an ideal truss, in practice, loads are typically imposed along the chords, resulting in a mixture of axial stress, bending moments, and shear (Engineer, 2020).

3.1 Types of Roofs Truss

- **Pitched roof trusses:** These are the most popular roof trusses. The top chord is sloped to allow for natural drainage of precipitation and removal of dust/snow accumulation. Because of this, even though the total bending impact is greater at mid span, the chord member and web member stresses are smaller closer to the mid span and larger closer to the supports. Figure 3.1 includes information such as span, purpose, site usefulness, cost, manufacturing time, the designer's own competence, and many more. A few examples of common truss configurations are provided below. Trusses such as the Fink, Pratt, Howe, and Fan fall under this category.

- **Parallel chord trusses** are used in multi-story buildings to support north light roof trusses, intermediate span bridges, prefabricated floor joints, beams, and girders.

- **Trapezoidal trusses:** In the event of particularly long span pitched roof trusses with depth at the ends are utilized.

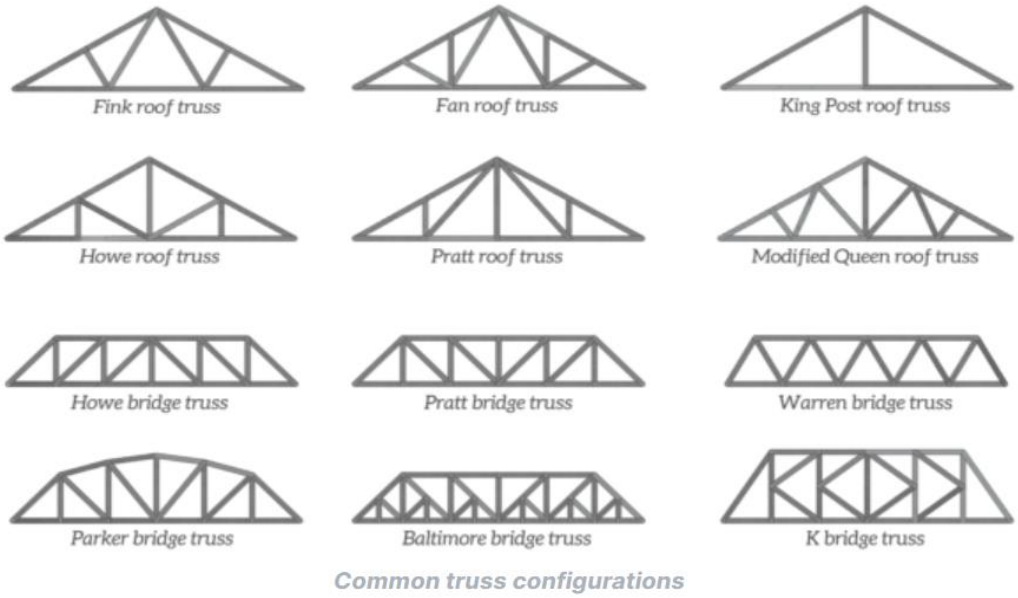

Figure 3.1 Different Types of roof trusses (Engineer, 2020)

3.2 Connections

Connections are necessary in constructions because they carry weights from one section to another. Analyses of past failures have revealed the crucial role played by connections in several cases of structural failure or collapse. When constructing with lumber, it's crucial to ensure that the joints have sufficient flexibility to support the weight of the structure (Fink et al., 2016). Many different types of timber connections, from those used in traditional carpentry to more modern glued-in rod timber joints, are utilized to fasten the various structural components of a timber building together. There are primarily three types of relationships to consider while organizing the connections:

- Traditional carpentry joints: joints are characterized by connecting timber elements without the use of external fasteners and rely instead on fitting two timber members together.
- Dowel-type joints: the most common connection type used in practice are dowl-type joints thesis joints connect two or more structural elements together by way of external fasteners often made of either wood or steel.
- Adhesive joints: are uncommon due to the lack of practically of gluing on the building site where external factors such as weather can severely degrade the integrity of such connections.

3.2.1 Punched metal plate fasteners

The nail plates used in conjunction with punched metal plate fasteners form an integrated system.

Nails are made by pounding them straight out of a steel plate see Figure 3.2. As a result of the punching process's constraints, the original steel plate's thickness cannot exceed 2 mm, hence the 'nails' have a relatively low carrying capacity. 'Nails' range in size from

8 mm to 15 mm. The most prevalent application of punched metal plate fasteners is in the fabrication of timber trusses.

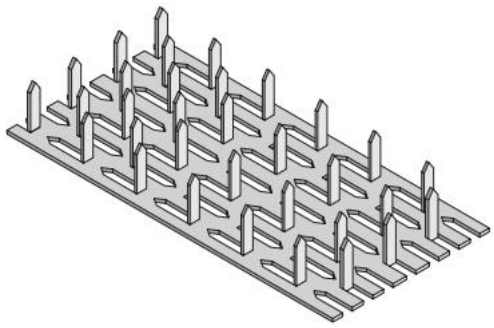

Figure 3.2 Punched metal plate fastener(Swidish wood, 2016)

3.3 Designing of Roof Trusses

The processes of producing solid wood and designing roof beams are now disconnected and have little mutual influence. So, when making the beams, construction workers must think about the wood's typical strength. As a designer at a roof truss manufacturer, you'll be responsible for conceptualizing and designing the truss from scratch, considering aspects like the building's intended use, size, and geographic location. Because of this data, the truss will be constructed differently.

The truss's final shape might shift later based on whether it is to remain concealed from view from within the structure. As soon as the truss design is finished, the blueprints are delivered to the manufacturing department where the truss components are cut and assembled. Located in Derome, this massive machine can be instructed to cut all the boards and members precisely and accurately for the truss, while also labelling them with the appropriate names. The assembly hall's ceiling will be outfitted with a laser to ensure that the truss sections are laid out at the correct distance and angle before being connected. Steel plates are added to the truss and the wood is firmly linked to the steel using a hydraulic pressure machine once the truss has been set up correctly. When the members are attached on one side of the truss, they are flipped over and connected on the other.

3.4 Loads on Roof Trusses

All the gravity or vertical loads acting on the building trusses are first calculated in terms of the loads acting per one square meter of the horizontal projected area. The wind loads are calculated per square metre of the actual inclined roof surface.

3.4.1 Dead Loads

Dead load is the self-weight of different components of the structure itself. Its magnitude and point of application do not appreciably with time. Dead loads on a truss comprise of loads of roof covering, perpendicularly running beams (purlins), connections, supporting elements (braces) and self-load of the truss. Therefore, to calculate an area load or line load, we need to know the density and size of each component. Density of a timber construction is assumed to be 5 percent, which is the

same as the typical value of wood strength. To calculate the truss's permanent load, it is required to know how much wood was utilized.

3.4.2 Snow Loads

Snow load is calculated according to maximum expected depth of snow in prearticular locality and density of snow.

This thesis will concentrate on a building in Gothenburg that has a typical snow load of $S_k := 1.5\frac{kN}{m^2}$ The frequency of this snow load is estimated to be around once per fifty years. The quantity of snow that accumulates on a roof is affected by both the snow zone and the roof's inclination; a steeper inclination means less snow will collect there, and vice versa(Boverkets, 2019).

A roof's angle affects the form factor used to translate the usual snow weight; to understand how this is done, refer to Figure 3.3. There are two probable causes of a saddle roof, the first being that the roof slopes toward the house's leeward side, which prevents snow from easily rolling off. This is how the windward side of the building is shaped.

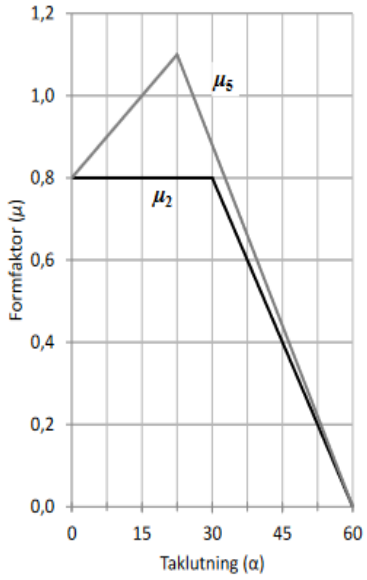

Figure 3.3 Coefficient to translate snow load on the ground to the rooftop depending on the roof angle(Boverkets, 2019)

3.4.3 Wind Loads

The force of the wind is always perpendicular to the plane of a building's exterior walls or roof. Once every fifty years, the roof is predicted to be hit by wind load equal to the average velocity pressure during a ten-minute period. The highest recorded speed was in Gothenburg, at 25 m/s (Boverkets, 2019).

Design wind pressure $P = Ce * Cg * qs * Iw$

Where Ce is the combined height, exposure, and gust coefficient.

In open areas and for height up to 10m $Ce = 1.25$

10 to 20m $Ce = 1.45$

20 to 30m $Ce = 1.61$

Value of pressure Coefficient Cg

Windward roof θ=0° to 9.5° $Cg = 0.7$ outward(-)

θ=9.5° to 37° $Cg = 0.9$ outward or 0.3 inward(+)

θ=37° to 45° $Cg = 0.4$ inward

>45° $Cg = 0.7$ inward

Leeward or flat roof $Cg = 0.7$ outward (-)

Windward walls 0.8 inward up to 6m height

0.87 inward for 6m to 12m height

1.0 inward for 12m to 18m height

Leeward walls 0.5 outward up to 6m height

0.54 outward for 6m to 12m height

0.63inward for 12m to 18m height

3.5 Selection of Member of roof trusses

The top chord members of roof trusses often consist of one section which contains through several panel points. This may be designed for the maximum force in any of the parts in which it is continuous. This practice may seem to be uneconomical but considering the resulting saving in the cost of splices, the result may be an economical design. if splices must be made at certain points for shipping or handling purposes, size may be economically changed at those points.

3.6 Selection of Truss Member using Angle selection

For top chord members that are adjacent to each other and have a force that is 25% less than the maximum of these members, the same section that is intended for the maximum force might be utilized. This is also applying to bottom chord members.
All top and bottom chord members should be double, and all compression members should be double angles. Web tension members may be single or double angles

depending upon the magnitude of force the zero-force member should be single angles and spacing should be calculated for all double angle selections.

3.7 Structural Reliability

Civil engineering structures are highly associated with structural reliability and reliability-based design to refer to probabilistic measures of safe performance of the structure (member or system) in a particular limit state or until an ultimate failure or unserviceability such as collapse, deflection, or cracking (Rosowsky, 1999)

Compared to weight, timber is a light material. However, the strength is high, and the strength-to-weight ratio is even higher than for steel (Köhler, 2007) Nonetheless, timber is not considered as a competitive building material compared with other construction materials such as concrete, steel, or masonry by many architects and structural engineers as features such as reliability, serviceability, and durability aren't associated with timber as a construction material (Köhler, 2007) Regardless, timber is a highly sustainable material in terms of production, use, and demolition throughout the life cycle of the timber structure (Köhler, 2007) Structural reliability analysis aims at quantifying the probability occurrence of such of failure.

3.7.1 Objective of Structural Reliability

The purpose of analysis is to quantify the probability of failure, or Pf, of a mechanical system with respect to a defined failure criterion. This involves taking into consideration the uncertainties that arise from the geometry, the material properties, and the applied load. The idea of the failure criteria may be characterized as the conflict that arises between two essential quantities, which are referred to as the "Demand" and the "Capacity" of the system, respectively. In the field of mechanical engineering, the term "Demand" refers to the action effects that produce a realization of a mechanical condition such as stress or displacement. In other words, demand is an action effect. The term "Capacity" refers to the strength of the material, which sets a limit state that must be adhered to prevent the collapse of the building.

4 Numerical modelling

The FE-software, RFEM-design 6, 2D *structure* is used to numerically solve different questions. The different equations in total describes the structural behaviour of the roof truss. This chapter intends to present the numerical modelling and validate its output.

4.1 Basic Assumptions

Many assumptions must be made to build a model that may be the subject of a structural analysis. In addition to taking the software's limitations into account, certain assumptions are made to simplify the study. The truss is held by pined supports, which limit movement in the support nodes both vertically and horizontally.

4.2 Finite element model

The structural 2D model of the W-type roof truss was built using the RFEM beam element see Figure 4.1. The model was built with the truss height and depth fully changeable, however, for analytical reasons, a height of 3meters and width of meters would be utilized. The slope was set to 30°.

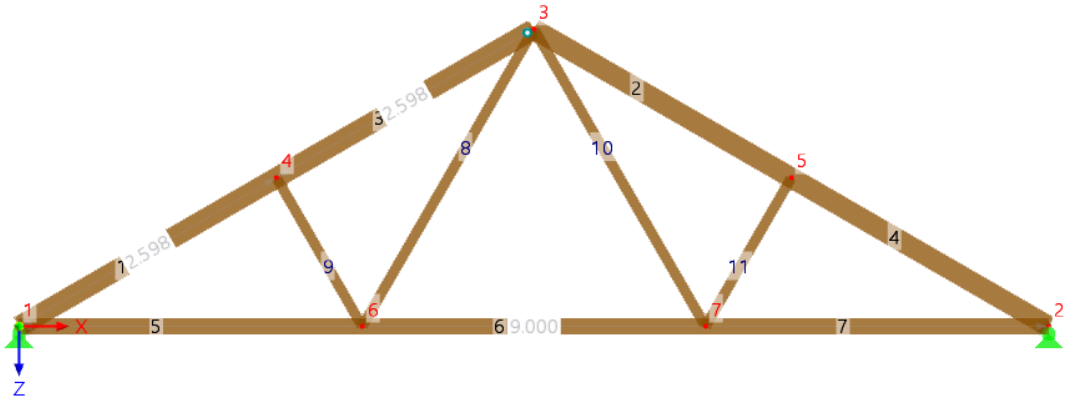

Figure 4.1 FEM model of roof truss of W-type

4.2.1 Material

The structural system in RFEM- Design is modelled based on materials on the market. C24 solid timber are used to for internal and external part with different thick is assigned to beams and trusses. Corresponding material properties can be seen in Table 4.1.

Table 4.1 Characteristic strength and stiffens properties used for structural roof timber material according to EN 338:2016.

C24	$f_{m,k}$ [N/mm²]	$f_{t,0k}$ [N/mm²]	$f_{t,90,k}$ [N/mm²]	$f_{c,0,k}$ [N/mm²]	$f_{c,90,k}$ [N/mm²]	$f_{v,k}$ [N/mm²]	$E_{0,mean}$ [KN/mm²]	$E_{90,mean}$ [KN/mm²]	$E_{0,05}$ [KN/mm²]	G_{mean} [KN/mm²]	ρ [kg.m³]
-	24	14.5	0.4	21	2.5	4.0	11000	370	7400	690	420

4.2.2 Material property distribution

Working with material qualities always involves a degree of uncertainty. Most building qualities are localized and not always of the same value. Therefore, other statistical measures, such as probability density functions and cumulative density functions, can be utilized and displayed.

4.2.2.1 Property Density distribution

A Probability Density Function (pdf) is utilized to represent the characteristics of a material. The form of the curve is determined by the mean and standard deviation. The standard deviation is the degree of dispersion of the distribution around the mean, and it is often denoted by the square root of the variance. With increasing standard deviation, the ascent of the parabola increases in height. The sum under the graph is 1, with data along the x-axis and probability density along the y-axis. The curve can depict the different probability density distributions versus tensile strength for C24.

4.2.2.2 Cumulative Distribution Function

Another method for representing distribution is the Cumulative Distribution Function (cdf). The cumulative distribution function is the integral of the probability density function. As a result, its values range from zero to one, unlike the probability density function. In some distributions, the median value occurs when the y-axis equals 0.5 and is also the mean. Similarly, the 0.95-quantile corresponds to the x-axis value when the y-axis is 0.95. The curve can depict the different cumulative distributions versus tensile strength for C24.

4.2.3 Connections & cross-section

A roof truss is a framework constructed between two supports and designed to withstand wind, precipitation, and the weight of the building's occupants. In contrast to other truss designs, the roof of a truss structure is typically inclined from the joists to the apex. Besides the top, bottom, diagonals, and top chord, there are also connections. In statics, the top and bottom chords behave like beams, bearing normal, shear, and bending moments, whereas the diagonals frequently behave like bars, bearing only normal pressures. Without the semi-rigid connections between sections in the RFEM, which prevent rotation and distortion in the unloaded state, components 5,6, and 7 (and 1,3, and 2) would be one continuous member along the length of the truss condition. The cross-sections and materials of the nodes and lines in an RFEM model are distinct. The designation of materials and cross sections to nodes and lines is possible with an RFEM model see Figure 4.2.

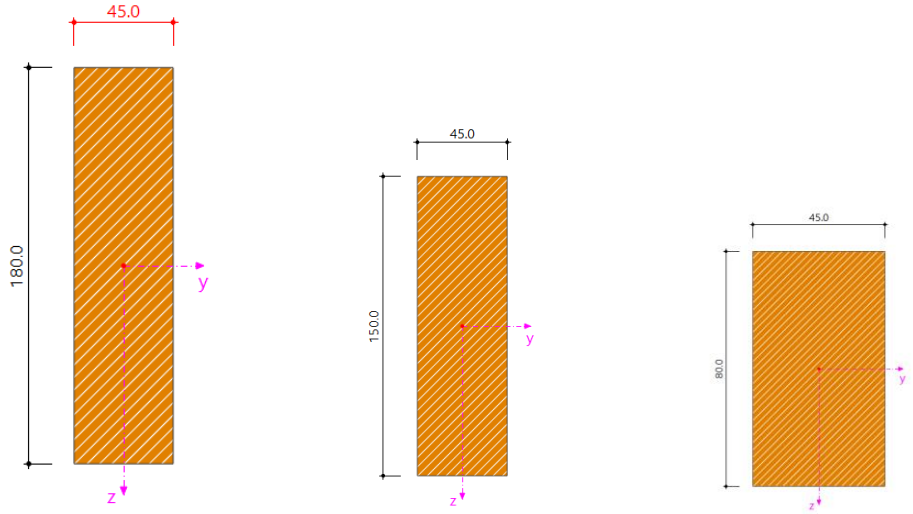

Figure 4.2 RFEM-design with material C24 with different cross sections

4.2.4 Loads

The structural loading origins from dead, imposed and wind loads. An imposed load of 4.155 kN/m^2 is assigned. A line load of 1.06 kN/m^2 is applied on the roof must bear. For the sake of clarity, it has been assumed that the bottom of the truss does not contain any ventilation system or other necessary equipment, as well as any ceiling, while discussing roofing material, insulation, and wood wool panels.
The wind loads are generated after the reference wind speed and terrain category are defined. A wind speed of 25 m/s is used assuming the roof is in Gothenburg. The Appendix contains all required computations of loads on roof.

4.3 Monte Carlo Simulation

Stress analyses assign each truss member. A material strength based on the normal distributions shown. The normal stresses in each component are then compared to the material strength. If the normal stress in a member exceeds the material strength, then the member has failed, and the corresponding position in a vector will be set to 1. Each component's failure rate is tracked during the simulation and then summarized at the end. Next, it gives as the percentage of total iterations that failed. As a function of iterations, the rate of failure squared. In this study, 1,000,000 iterations of a Monte Carlo simulation were run.

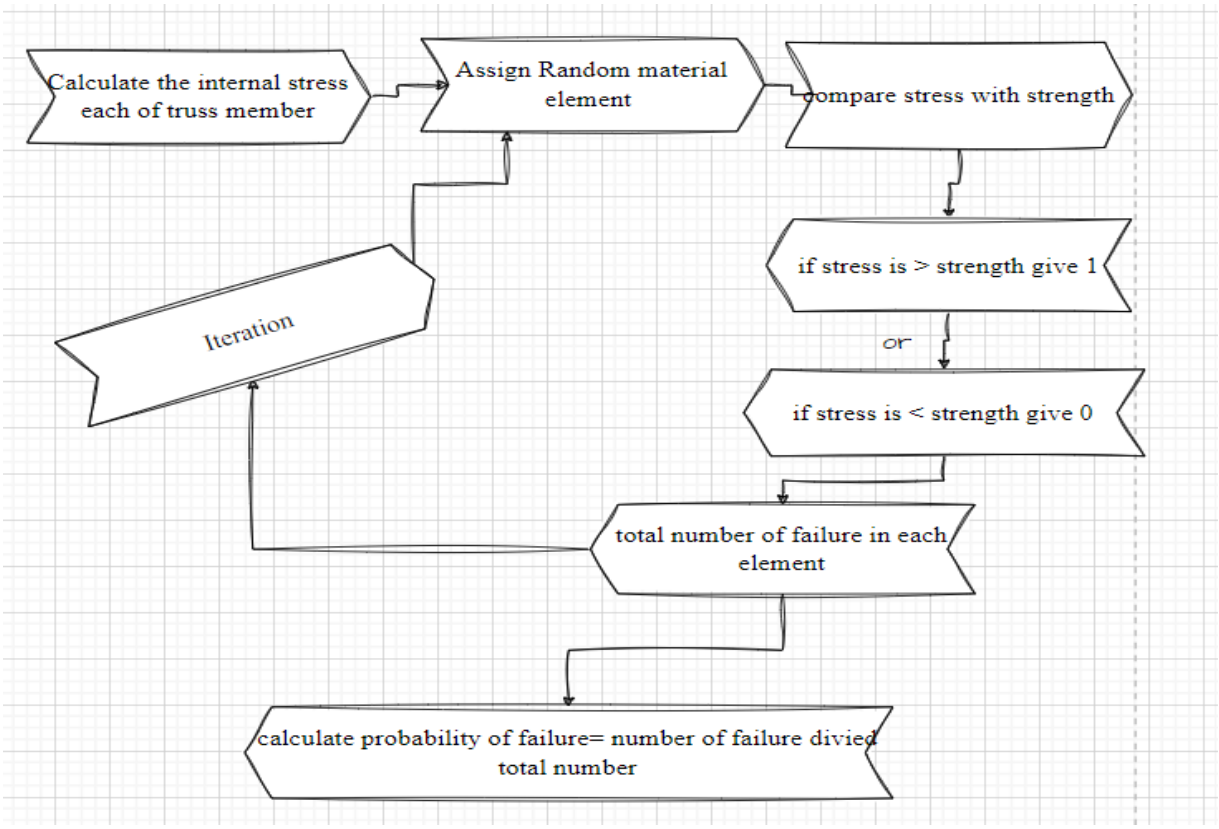

Figure 4.3 Flow chart for reliability analysis based on Monte Carlo method.

4.4 Optimization by using Monte Carlo

Additionally, the Monte Carlo simulation is executed with optimal member placement as opposed to random placement. The distributions are used to create eleven distinct material strengths, ranked from weakest to strongest. Then, these materials are assigned to elements based on the stresses to which they are exposed. The weakest material is assigned to the least stressed member, the strongest to the most stressed, and so on.

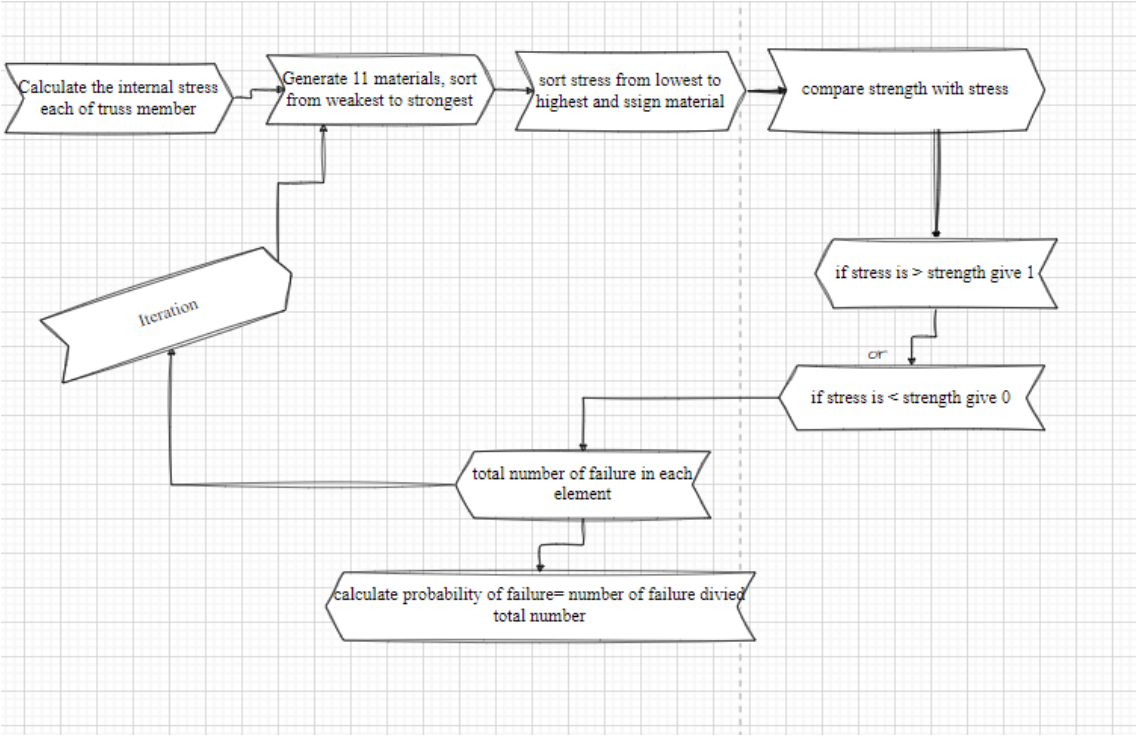

Figure 4.4 Flow chart for optimization based on Monte Carlo method.

5 Results and Discussion

This charter provides and discusses the results of the Monte Carlo simulation performed in MATLAB, the appropriate cross-sectional dimensions for each truss type, as well as the benefits and drawbacks of changing size or grade.

5.1 Random Iteration

In the most cases sufficient to test three different board dimensions with varying width and thickness. The range of board permitted to be graded based on derived setting is #10% of the tested sizes. The sample consists of 100 boards includes the given dimension 45*180,45*150 and 45*80mm (see Table 5.1).

The inputs that changed with each iteration included cross-sectional view of the members and their unique allocated material which in this case is C24.

Table 5.1 Dimension of memebrs used

Members	***Height(mm)***	***Width(mm)***
Top chord (1,2,3&4)	180	45
Bottom chord (5,6&7)	150	45
Diagonals (8,9,10&11)	80	45

The data obtained through simulations makes sense. Because normal stresses increase with decreasing cross-sectional size and material, the likelihood of failure increases as the cross-sectional size of each member decreases. If one or more members of a truss failed under the applied load, the truss was deemed to have failed. In the simplest terms, an object fails when the stress it is subjected to exceeds its strength. In this context, fortitude is failure resistance.

5.2 Material

In this thesis, the computer-generated Monte Carlo simulation results follow a normal distribution. Over ninety-five percent of the sample values for these materials surpass 24 MPa. The sample consists of 100 data points, but the distribution resembles a log-normal probability distribution as seen Table 5.2. The material properties can be allocated to each individual component.

Table 5.2 Material properties used.

Material properties	***Distribution***	***COV***
Tensile strength f_t	Lognormal	0.25

Probability and cumulative density function in Figure 5.1 and Figure 5.2 illustrate graphically how to combine the patterns. The probability density distribution and Cumulative distribution function of in tensile strength is shown for C24 solid timber it can be seen significate difference. The 5th percentile of tensile strength is 14.5 N/mm^2, 50th percentile of tensile strength is 21.5 N/mm^2 and 95th percentile of tensile strength is 32.6 N/mm$^{2.}$

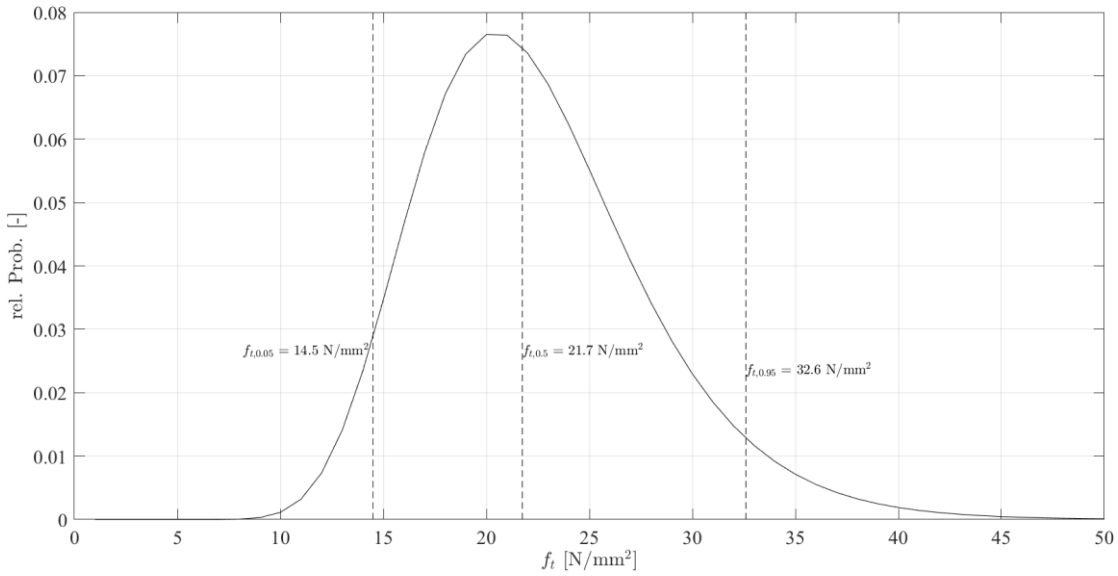

Figure 5.1 Probability density distribution of the tensile strength for C24 structural timber with the 5%, 50% and 95% fractals.

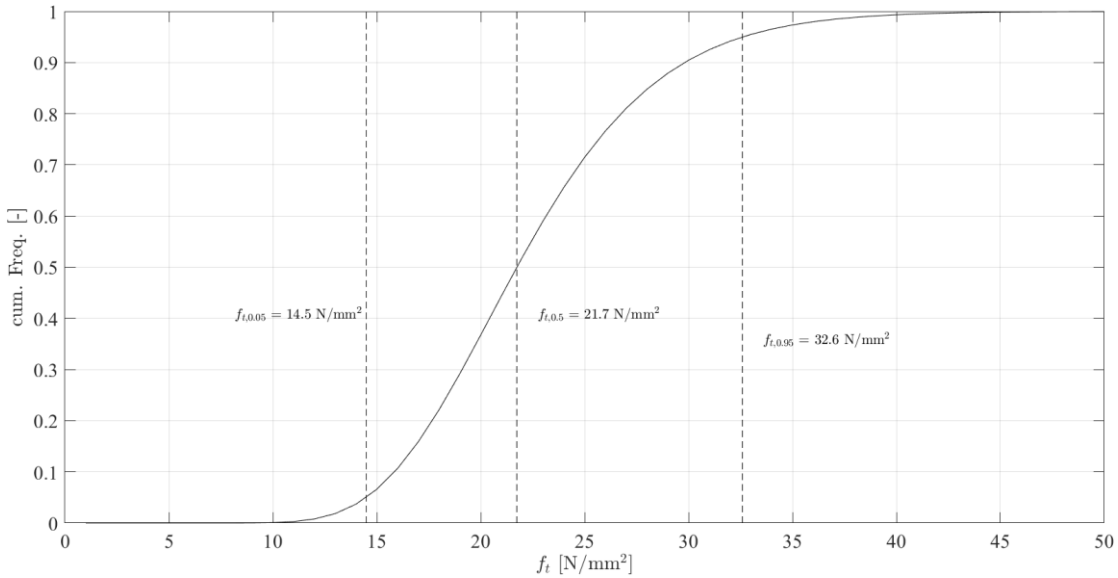

Figure 5.2 Cumulative distribution of the tensile strength for C24 structural timber with the 5%, 50% and 95%.

5.3 Load

To evaluate the influence of timber property correlations on roof truss dependability, the natural fluctuation of truss loads must be considered. Current design strategies employ real load numbers to account for load volatility. Because there is a tiny probability that the real load may be surpassed over the structure's service life, designers accounted for this while calculating the nominal load values.

While nominal loads of this magnitude are useful for truss design, they should not be employed in a roof truss dependability study. Failure evaluations cannot be restricted to a single point on the load distribution and must encompass the whole load distribution for correct modelling of the load-resistance interaction.

Each load type has its own load factor that considers. the precision with which the load is estimated and any variations that may occur during the structure's service life. Because the degree of uncertainty in calculating dead loads is lower than in evaluating live loads, dead load factors are lower.

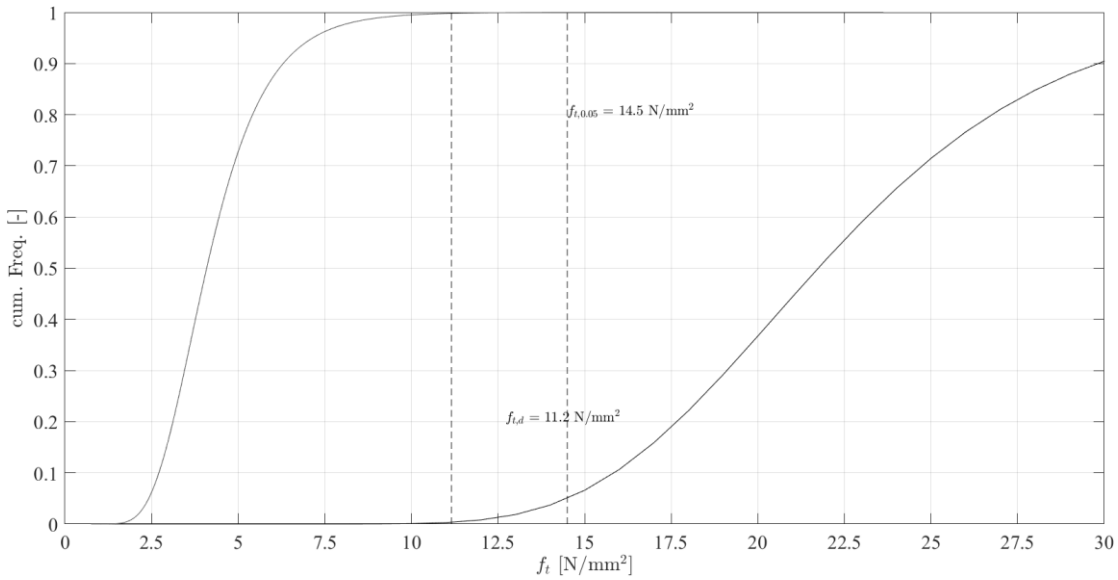

Figure 5.3 Cumulative distribution of load with tensile strength.

5.3.1 Load and strength of material in the members

Stress and strength are not constant but vary between the members. Stress varies because of loading cycles while as strength varies because of material variations, deterioration due to aging, corrosion, temperature etc.

In case both stress and strength are normally distributed and model the joint distribution of the difference.

Figure 5.4 demonstrates that, even though the mean strength is greater than the mean stress, there exists a region where the distributions overlap, and the stress can in fact exceed the strength and contribute to a portion of material failure. The region is known as the interference region, and from a qualitative standpoint, the existence of this interference religion imposes a failure probability on the design.

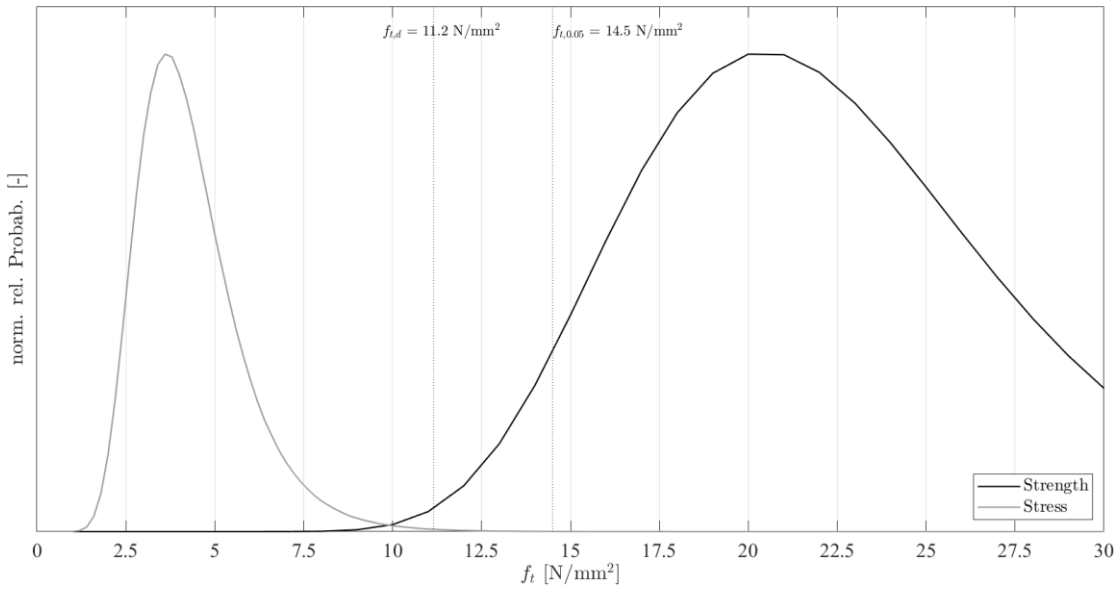

Figure 5.4 Stress and strength distribution.

5.4 Results Monte Carlo

Results from Monte Carlo simulations can be seen in Table 5.3 the risk of failure greater than 1/1,000,000.

Table 5.3 Failure of the whole truss any of the 11 members.

METHOD	***MEMBERS***	N_{CALL}	P_F
MCS	1	2137	2.1370e-04
	2	298	2.9800e-05
	3	105	1.0500e-05
	4	56	5.6000e-06
	5	31	1.0000e-06
	6	24	2.4000e-07
	7	17	1.7000e-06
	8	12	1.2000e-06
	9	9	9.0000e-07
	10	7	7.0000e-07
	11	5	5.0000e-07

A total number of individual member and truss failures were recorded. For each combination of residual correlation coefficients, the failure probability was determined by dividing the number of failed trusses by the total number of trusses. Any other outcome would indicate a defect in the structural or statistical model, which is not the case. In this thesis, the number of failures increases proportionally with the number of

iterations performed; however, 1,000,000 iterations are predicted to be sufficient to generate credible findings regarding failure risk.

The failure probabilities calculated for each truss member based on Monte Carlo simulation for the material C24 are displayed in Table 5.3 the probability of failure for all 11 members based on the limit state equation.

5.5 Optimized Placement

In addition, a Monte Carlo simulation and optimal material arrangement analysis are performed. The analysis is conducted using the dimensions.

Table 5.4 demonstrates that when eleven members are randomly selected from the batch of boards and inserted into a truss according to their strength, the probability of failure for trusses with a strength class of C24 is significantly reduced.

Table 5.4 Optimization whole truss any of the 11 members.

Method	***Members***	N_{call}	P_f
MCS	1	475	4.7500e-05
	2	24	2.4000e-06
	3	7	7.0000e-07
	4	3	3.0000e-07
	5	1	1.0000e-07
	6	1	1.0000e-07
	7	0	0
	8	0	0
	9	0	0
	10	0	0
	11	0	0

As seen in Figure 5.5 we investigated uncertainty in our thesis study. The optimization problem under varying uncertainty is characterized by the obligation to make judgements without understanding their full consequences. The illustrations depict several terms of uncertainty that are expressed in various truss members.

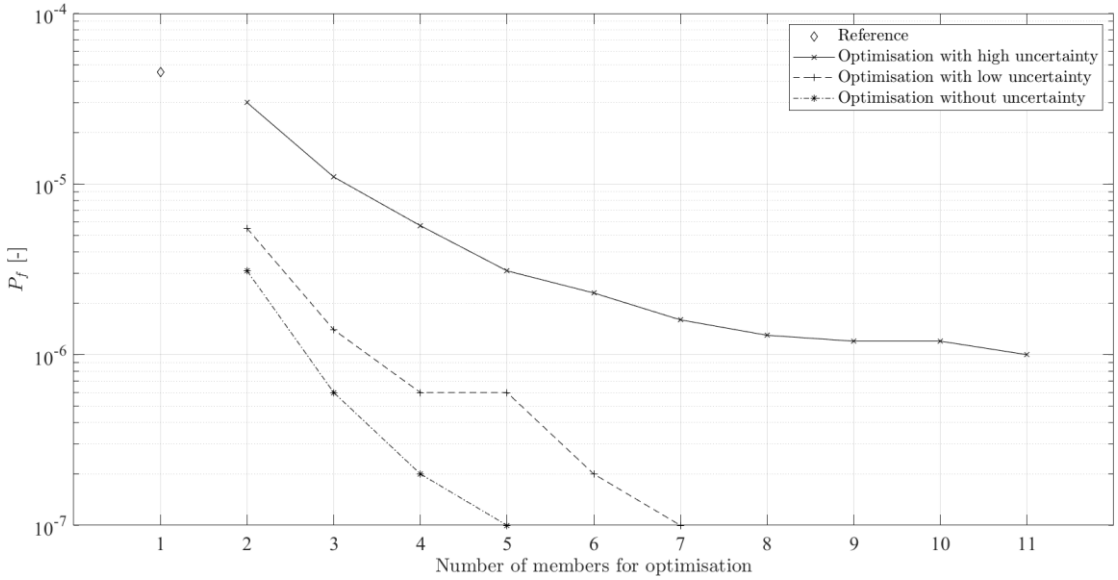

Figure 5.5 Optimization with corresponding to various levels of uncertainty.

5.6 Drawbacks of changing size or grade.

According to the data, the size of the members has a greater influence on the risk of failure than the grade of the timber. When the strength of the timber is modified, the stresses vary insignificantly, but when the dimensions of the member are changed, the stresses significantly rise. If the cross-sectional area of the member is cut in half, the stress in the member is doubled. The most effective technique to improve the structural soundness and efficiency of the truss is to change both the size and the strength of the timber.

5.7 Assumptions

The most frequent failure in trusses is a failure in the steel plates, however, in this study, the plates is assumed not to be failing and only the timber members to be susceptible to failure. When evaluating the obtained data, it is important to keep in mind that it is not feasible to assume that the steel plates would not fail. Steel plates and wood members may both be designed using RFEM software. This can also be used to reduce the risk of failure for both steel plates and timber members. To obtain more information it is possible to alter the material size and classes of each component independently.

6 Conclusion and need for further studies

The purpose of the thesis was to determine if timber trusses can be optimized if data from testing and grading can be incorporated into their design. This objective has been accomplished, as we have demonstrated that it is possible to reduce the probability of failure by utilizing optimized and deliberate material placement.

The many criteria used to explain truss behaviour have been assembled and utilized to create computer models to replicate truss pattern behaviour. To evaluate roof truss dependability state-of-the-art methodologies were utilized to create load and resistance which were then employed together with the suggested failure condition except for the amount of correlation among strength residuals, the system parameters for the truss remained constant between simulations as a result the impacts of strength property correlations on roof truss dependability were studied. According to the results, there are measures that can be taken to improve the efficiency of designing and constructing timber trusses.

For the structural system of a timber roof truss, the limit state function can be defined as a function considering many variables (load components, resistance parameters, material properties, dimensions, and analysis factors) which are uncertain. These uncertain variables have been treated as a random variable using reliability-based approach.

In this thesis the Monte Carlo method was used for estimating the reliability of structural system and it has been shown that the method allows to estimate the reliability of the structural system with a moderate computing work. It has been demonstrated that the approach may yield reliable estimations of structural system.

Timber is not a homogenous material, and if grading data can be utilized in the designing process, trusses can be constructed more efficiently and with a reduced risk of failure. Although the structural integrity of the truss can be assumed to be of higher quality when designing according to the testing data, rather than relying solely on the tabulated strength classes, there may be a greater risk of human error, necessitating more stringent inspections of the trusses prior to their installation.

6.1 Need for further studies

Additional research might be done to examine the truss nailing plates and joints. The most frequent failure in a genuine truss is the failure in and around the metal nailing plates, nevertheless, in this research the possibility of this failure has been ignored. There are several additional truss types that may be studied; however, this thesis has only looked at a Fink truss. Further analysis and optimization may be achieved with other and more complex truss types and should be analysed in future research. Since Fink trusses are only a special truss type and not used on every roof, evaluations of different truss forms are required. For example, in Sweden when building a half-story dwelling, the timber roof truss may be used as formwork instead and these trusses are subjected to different stresses and loads. In the Monte Carlo simulation in this paper only the normal stresses of individual members were considered, which is a strong limitation and should be enhanced in further studies.

7 Bibliography

1. Boverkets. (2019). *Boverkets konstruktionsregler EKS 11. Retrieved September 27, 2023, from www.boverket.se/publikationer—*

2. Deublein, M., Steiger, R., & Köhler, J. (2010). *Quality Control and Improvement of Structural Timber*.

3. Engineer, E. (2020, November 19). Understanding and Analysing Trusses. *The Efficient Engineer*. https://efficientengineer.com/trusses/

4. Fink, G. (2014). *Influence of varying material properties on the load-bearing capacity of glued laminated timber* (p. 144 p.) [Application/pdf]. ETH Zurich. https://doi.org/10.3929/ETHZ-A-010294974

5. Fink, G., Jockwer, R., & Kohler, J. (2016). Reliability based design of timber structures – system focussed application. *Proceedings of the World Conference on Timber Engineering (WCTE 2016)*, 3702–3709. https://research.aalto.fi/en/publications/reliability-based-design-of-timber-structures-system-focussed-app

6. Fortuna, B., Plos, M., Šuligoj, T., & Turk, G. (2018). *Strength grading of structural timber*. https://doi.org/10.31534/CO/ZT.2018.09

7. Hansson, M., & Thelandersson, S. (2003). Capacity of timber roof trusses considering statistical system effects. *Holz Als Roh- Und Werkstoff*, *61*(3), 161–166. https://doi.org/10.1007/s00107-003-0373-x

8. Harte, A. (2009). *Introduction to timber as an engineering material. In M. Forde, ICE Manual of Construction materials. Galway: ICE.*

9. Jockwer, R. (2020.). *Timber engineering 2020*. Retrieved 10 June 2023, from https://chalmers.instructure.com/courses/9003/pages/lecture-1

10. Köhler, J. (2007). *Reliability of timber structures* (p. 212 S.) [Application/pdf]. ETH Zurich. https://doi.org/10.3929/ETHZ-A-005454370

11. Ravenshorst, G. (2015). *Species independent strength grading of structural timber*.

12. Ridley-Ellis. (2016). *Grading structural timber. Edinburgh, Scotland* -.

13. Ridley-Ellis, D., Stapel, P., & Baño, V. (2016). Strength grading of sawn timber in Europe: An explanation for engineers and researchers. *European Journal of Wood and Wood Products*, *74*(3), 291–306. https://doi.org/10.1007/s00107-016-1034-1

14. Rosowsky, D. V. (1999). *Structural Reliability*.

15. Swedish Wood. (2015). *Design of timber structures (Vol. 1). Stockholm: Swedish wood._*

16. Swedish Wood. (2016). *Grading of sawn timber in Europe according to EN 1611-1*.

17. Swedish Wood. (2016b). *Wood grades*. Swedish Wood. https://www.swedishwood.com/wood-facts/about-wood/wood-grades/

18. *TräGuiden*. (2017). Retrieved 26 October 2023, from https://www.traguiden.se/konstruktion/limtrakonstruktioner/projektering-av-limtrakonstruktioner/bruksgranstillstand/statiska-deformationer/deformationer/

19. Victor, O. (2020). *Timber as a Structural Material*. STRUCTURES CENTRE. https://structurescentre.com/timber-as-a-structural-element/

8 Appendix

Input Data

$L := 9m$ Length of roof truss:

$L_1 := \frac{L}{3}$ Distance between chord and web members:

$\alpha := 30deg$ Angle of top chord:

$H := \tan(\alpha) \cdot \frac{L}{2} = 2.598m$ Height of roof truss:

$H_1 := \frac{H}{3}$ Height where outer web member attached to top chord:

$d := \sqrt{\left(\frac{L}{2}\right)^2 + H^2} = 5.196m$ Length of top chord:

$b := 45mm$ $h := 200mm$ Dimensions of members:

$cc := 1200mm$ Assumed center to center distance between roof truss:

Material Parameters

Timber C24

Bending strength parallel to grain	$f_{mk} := 24MPa$	
Density of Timber	$\rho_k := 350\frac{kg}{m^3}$	
Safety Factor	$\gamma_m := 1.3$	EC5 Table 2.3
Modification Factor	$K_{mod} := 0.8$	Solid timber, Medium term load, SC2 EC5 Table 3.1

$$f_{md.uls} := \frac{K_{mod} \cdot f_{mk}}{\gamma_m} = 14.769MPa$$

Loads

1.Self -weight of roof

Volume of roof truss:

$$V := L\cdot b\cdot h + \frac{L}{2}\cdot\cos(\alpha)\cdot b\cdot h\cdot 2 + 2\cdot\sqrt{\left[\left(\frac{L}{2} - L_1\right)^2 + H^2\right]}\cdot b\cdot h + 2\cdot\sqrt{\left[\left(L_1 - \frac{H_1}{\tan(\alpha)}\right)^2 + H_1^2\right]}\cdot b\cdot h = 0.24\,m^3$$

Assumed self-weight of roof truss negligible.

$$\rho_k = 350\frac{kg}{m^3} \qquad g = 9.807\frac{m}{s^2}$$

$$g_{ktruss} := \frac{\left(V\cdot\rho_k\cdot g\right)}{L} = 0.09\cdot\frac{kN}{m}$$

Assumed self-weight of the roof according to from www.traguiden.se:

$$g_{krooftop} := 0.8\frac{kN}{m^2}$$

self-weight of roof on each truss:

$$g_{krooftop} := g_{krooftop}\cdot cc = 0.96\cdot\frac{kN}{m}$$

self-weight of roof structure:

$$g_k := g_{ktruss} + g_{krooftop} = 1.05\cdot\frac{kN}{m}$$

2.Snow Load of Roof

Gothenburg

$$S_k := 1.5\frac{kN}{m^2}$$

Angle of pitch of roof

$$\alpha := 30$$

Factor regarding angle of roof

$\mu_2 := 0.8$ assuming the lower roof is flat

$\mu_5 := 0.87$ shape coefficients

snow load on roof top

$S_2 := S_k \cdot \mu_2 = 1.2 \frac{kN}{m^2}$

$S_5 := S_k \cdot \mu_5 = 1.305 \frac{kN}{m^2}$

snow load on each roof truss

$q_{ksnow.2} := S_2 \cdot cc = 1.44 \frac{kN}{m}$

$q_{ksnow.5} := S_5 \cdot cc = 1.566 \frac{kN}{m}$

3.Wind Load of Roof

$V_b := 25 \frac{m}{s}$ wind speed in Gothenburg

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

$q_b := \frac{1}{2} \rho_{air} \cdot V_b^{\,2} = 390.625 Pa$ mean velocity of wind pressure

Assume terrain III and building height 12m.

$K_r := 0.22$ $z_0 := 0.3$ $Z := 12$

$c_e := \left(K_r \cdot \ln\left(\frac{Z}{z_0} \right) \right)^2 \cdot \left(1 + \frac{7}{\ln\left(\frac{Z}{z_0} \right)} \right) = 1.908$

Terrain and building factor of height.

Peak velocity of Pressure

$q_p := c_e \cdot q_b = 745.473\,Pa$

External Pressure Coefficient

$$c_{pe.10} := \begin{cases} 0 \text{ if } \alpha < 5deg \\ 0 + 0.2 \cdot \frac{\alpha - 5}{15 - 5} \text{ if } 5deg < \alpha < 15deg \\ 0.2 + 0.5 \cdot \frac{\alpha - 15}{30 - 15} \text{ if } 15deg < \alpha < 30deg \\ 0.7 \text{ if } 30deg \le \alpha < 60deg \\ 0.7 + 0.1 \cdot \frac{\alpha - 60}{75 - 50} \text{ if } 60deg \le \alpha < 75deg \\ 0.8 \text{ if } \alpha \ge 75deg \end{cases} = 0.8$$

External pressure acting on roof. $w_e := q_b \cdot c_{pe.10} \cdot cc = 0.375 \frac{kN}{m}$

Ultimate Limit State Loads of Roof

Snow Load

$q_{d.snow.2} := q_{ksnow.2} \cdot 1.5 + w_e + g_k \cdot 1.35 = 3.953 \frac{kN}{m}$

$q_{d.snow.5} := q_{ksnow.5} \cdot 1.5 + w_e + g_k \cdot 1.35 = 4.142 \frac{kN}{m}$

Wind load

$q_{d.wind2} := q_{ksnow.2} + w_e \cdot 1.5 + g_k \cdot 1.35 = 3.42 \frac{kN}{m}$

$q_{d.wind5} := q_{ksnow.5} + w_e \cdot 1.5 + g_k \cdot 1.35 = 3.546 \frac{kN}{m}$

Designing load case, we use the largest load.

$$q_d := \begin{cases} q_{d.snow.5} \text{ if } q_{d.snow.5} \ge q_{d.wind5} \\ q_{d.wind5} \text{ if } q_{d.snow.5} < q_{d.wind5} \end{cases} = 4.142 \frac{kN}{m}$$