Multi-Storey Mixed-Purpose Timber Housing

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PREFACE

After my stay in Luleå I realised the importance of the timber structures for the future, and the people who helped me to understand and who I want to acknowledge are:

- Dr. Anders Björn fot and Gabriela Thustochowicz, who introduced me to timber structures, specifically in trä8 and volumetric system, and with their knowledge about timber constructions, in a theoretical and practical way, have helped me to write this Master’s Thesis.

- Ola Enochsson and Henrik Engelmark, for helping me with the challenges that using FEM-Design created.

- Ass. Prof. Helena Johansson, for helping me to understand volumetric system and how this construction system works.

- Moelven Byggmodul, which given to me the possibility of realise this innovative project.

Finally I would like to say that realise this Master’s Thesis abroad and meet these people who has given to me all the comprehension that I have about timber structures has been a great experience which has made me mature as a person and as an engineer.

_Luleå, January 2011_

_Tamara Carvajal Benitez_
MULTI-STOREY MIXED-PURPOSE TIMBER HOUSING

ABSTRACT

Since ancient years, wood has been an important construction material. In the Nordic countries, like e.g. Sweden, timber has an essential role and more than 90% of all single family houses are built with timber. Another situation is for multi-storey buildings where the market for timber is about 7% in Sweden, and most of these buildings are two-storey only. The reason for this is that timber has been disqualified for a long time in construction of multi-storey houses by restrictive fire regulations imposed after a number of Swedish cities were burned down in the late 19th century. Today the Swedish government has created a strategy to increase the use of timber in multi-residential and commercial buildings.

Nowadays, on the current Swedish market, there are three types of building systems for multi-storey timber buildings. The panel system is based on pre-fabricated planar building elements like walls or floor elements. The volumetric system is principally utilizing the light frame system or solid wood, and the whole volumetric units are assembled off-site and transported to the building site for erection. These systems are mainly used for residential buildings, student apartments, and buildings like schools and offices. The beam and post system is common for industrial and commercial halls because it is suitable for large span structures. It is a system based on a load-bearing net of beams and columns.

This Master thesis presents a conceptual and structural design of a multi-storey building combining two different timber based building systems. The first two floors will be built in a new post and beam system called trä8 developed by company Moelven Töreboda. The remaining three storeys will be built using volumetric modules. It will allow making mix buildings with large spans in the bottom of them, for commercial uses, and dwellings in the top part.

The used methodology consists in, firstly, some hand calculations to learn how to design in timber structures in a traditional/conservative way and, secondly, the computer calculations were performed with the use of Finite Element software, FEM-Design, to analyze the connection between trä8 and volumetric system. Moreover, literature study was performed to achieve the basic knowledge to perform the above calculations.

Key words: trä8, beam and post system, volumetric timber modules, multi-storey building, mix building, FEM-Design
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1 INTRODUCTION

Since decades, timber has been one of the most used structural materials but after the appearance of the concrete and the steel its use was decreased. In this chapter the history of timber as a construction material is resumed and the Master’s Thesis purpose is exposed.

1.1 Background

Timber structures have had a great importance along the history of the humanity. Since ancient years until today the use of the timber has been present daily. From Asia, with its Pagodas, to Europe, especially in the Nordic countries, timber is a widely used material which has found its place in the structural market of the whole world.


From one-family residential houses to road bridges, the timber versatility opens a wide range of possibilities. Despite of its large extension around the world and the history, the invention of cast iron reduced the use of the wood for large constructions, and particularly for larger residential buildings. The ease for appearance of uncontrolled fires, e.g. The Great Fire of London in 1666, and the great properties that steel and concrete posses, placed the timber construction in a second plane. Nowadays, it has been revealed that wood is a poor conductor of heat and, with effective fire prevention (insulation and compartments), it is not a problem for timber structures to resist the fire until the firemen arrive. This is the reason why, since 1990’s, the return of timber for large buildings is a fact.
In Sweden, timber construction has a long tradition and in recent years, structural timber systems are increasingly used in multi-storey and large span buildings. The use of timber in Swedish construction sector has been greatly influenced by governmental strategies and, due to it, the multi-storey timber construction started in 1996 with the traditional on-site 2” x 4” ("two by four"). Nowadays, on the Swedish market, there are three types of building systems for multi-storey buildings that can be divided with respect to the prefabrication degree into: panel system, volumetric modules system and beam and post system (including also frame structures). The panel system is based on pre-fabricated planar building elements like walls or floor elements (can be solid wood or light frame system). The volumetric system is principally utilizing the light frame system or solid wood, and the whole volumetric units are assembled off-site and transported to the building site for erection. These systems are mainly used for residential buildings, student apartments, and buildings like schools and offices. The beam and post system is common for industrial and commercial halls because it is suitable for large span structures. It is a system based on a load-bearing net of beams and columns.

1.2 Problem description

As it has already been indicated, panel and volumetric systems are mainly used for residential buildings whereas the beam and post system is intended to be utilised for industrial and commercial applications. The difficulty appears when it is necessary to build a building which requires longer span lengths in the bottom for commercial areas or offices, and dwellings at the top part. In the cities, it is common to see multi residential buildings with offices and commercial places at the bottom of the building, but the problem is that none of the timber based systems is suitable for both applications. Thus, often the first one or two storeys are built in concrete or steel.

1.2.1 Aim and scope

The purpose of this Master thesis is to design conceptually and structurally a 5 storey building combining two different building systems in timber. The first two floors will be built in a new post and beam system called trå8 developed by company Moelven Töreboda. The remaining three storeys will be utilizing the volumetric modules, built in the light frame system. It will allow making mixed purpose buildings with large spans in the bottom of them, for commercial uses, and dwellings in the top part. This will allow using timber in the whole building. One of the main goals of this thesis is to find an effective and functional distribution between the two systems. This is an important aspect of design because the two systems have different characteristics and limitations thus a compromise has to be found for achieving a successful application. The other, more personal goal, is my acquisition of knowledge about timber structures in one of the pioneering countries in this field.
1.2.2 Method

The used methodology consists of, firstly, hand calculations to learn how to design in timber structures in a traditional-conservative way. To design the structure, Eurocodes were used: Eurocode 1 for calculating wind and snow actions and Eurocode 5 for specific design of timber structures. Secondly, a numerical analysis was performed with the use of Finite Element software, FEM Design, to analyze the general behaviour of the building. Moreover, the extensive literature review was performed regarding timber engineering in general and the structural design of timber structures.

1.2.3 Limitations

Considering that timber construction is a large field, in this Master’s Thesis is analysed only the behaviour of a mix building composed by volumetric and trä8 system against actions and thanks to this analysis the stabilisation system of trä8 is design. Another point that has to be taken into consideration is that the analysis is only applied in one building as a test to prove the validity of it. To analyze the building with numerical software, due to its limitations, certain simplifications were assumed, the structure of walls in light frame system, stabilising elements and floors in system trä8 were represented by solid elements with strength and stiffness corresponding to the real structures.

1.3 Timber as a construction material

Timber is one of the oldest materials utilised for construction. It has a high strength to weight ratio, is capable of transferring both tension and compression forces, and is naturally suitable for flexural members [13]. As a material, timber has some characteristics that make it unique. One of the most important characteristics is that timber is an anisotropic material, which means that its properties are different for three different directions named longitudinal, radial and transversal. Normally, the grain direction is called the strong direction and, generally, it is parallel with the longitudinal axis of the stem. Wood is also a non-homogeneous material which contains natural defects which appear during the growth of the tree. This makes wood a structural material with a significant variability in its properties.
One of the main to create effective structures the mean point in timber structures is the connections between different elements, as for example, beams and columns. The way of make these connections is varied, from simple compression connections, as used mainly in the past, up to complex doweled joints (e.g. nailed or screwed). This variability permits to choose the best option in every case [16].

These are some of the essential characteristics that make timber a very good construction material. Also, if designed correctly, it can provide very durable with efficient solutions.
2 BUILDING SYSTEMS IN TIMBER

This section includes a brief description of building systems that were used in the project, beam and post system trä8 and volumetric timber modules build with light frame technique. Also used materials are described.

2.1 Volumetric module system

Volumetric timber modules are in use in Sweden since 1950s. The first buildings where this system was used were detached houses or standardised booths and barracks. Later, the system started to be used for schools and office buildings. Presently, in Sweden, around 30% of the detached houses are built with this system however, surprisingly, only 8% are the multi-storey buildings. Volumetric construction tends to lend itself more to multi-storey building due to the ease of repetition. However, remembering the strong restriction that took place in the previous centuries against multi-storey timber buildings, this fact is more understandable.

In 1994, with the introduction of the reformed Swedish performance based building code, the construction of multi-storey building was allowed again. Following this change, several timber volumetric modules manufacturers focused their investigations on developing new technologies which could permit reaching the multi-storey housing market. Nowadays this development has slowed down and only a few large-scale structural and functional innovations occur.

2.1.1 Materials

In general, the use of construction materials in the building depends on physical and energy-related requirements, and the quality demands. Due to this there is an extensive catalogue of materials that can be sort by the use of every part as a constructive element.

Timber frame is the main load-carrying part of the building and in case of light frame system is made with sawn timber (normally in Sweden: Norway spruce). This frame is composed of vertical members called studs, bottom and top rail. The spacing between the studs in the vertical plan depends on the arrangement of doors and windows, but the common centre-to-centre spacing in a standard wall is between 600 and 1200 mm.
The sheathing of the walls is important for the protection of the structure against weather but also plays a structural roll in stabilisation against horizontal loads. Normally, it is fabricated with paper faced gypsum boards, and if the larger shear capacity is required then one layer can be using wood-based board material as, e.g. OSB (oriented strand board). The materials used for inner and outer sheathing are similar, but their properties are adjusted for the purpose.

![Gypsum and OSB](image)

*Figure 3.2. Gypsum [3] and OSB [15]*

Insulation materials: are placed in between studs, e.g. mineral or stone wool.

![Mineral wool](image)

*Figure 3.3. Mineral wool [3]*

### 2.1.2 Concept

The system consists of a rectangular modules constructed with four load-carrying walls, a system of joists (floor), interior roof and a number of partition walls. The manufacture process that takes place in factory is following [14]:

1. The structure of the elements is finished.
2. Insulation and services are installed.
3. Boards are placed on the structure to seal out the elements and subassemblies like doors and windows are installed.
4. Once completed the elements for one volume are moved to a volume assembly station.
5. The wall elements are placed and fixed onto the floor and the roof is placed on top.
6. The volume elements are then completed with flooring, finishing, installations, wardrobes, cabinets and white goods are installed as required.
7. Finally, completed volumes are covered with moisture-proof canvas for the transportation.

One of the most important things that characterize the volumetric module system is that the most of the manufacturing is preformed in a controlled off-site environment that allows avoiding moisture and weather exposure, an usual risk related to the on-site erection. Another important point is that the size of volumes is optimized according to manufacturing, handling and transportation limitations, with the dimensions of 12x3 m.

2.2 Beam and post system

The beam and post system is a construction system that has been widely used in steel and concrete structures for ages. Often, when flexibility of the construction is desired, this system could be used as it allows for large span lengths, architectural freedom and simplicity. Nowadays, when the environmentally friendly materials are highly appreciated the beam and post system utilising engineered woods products becomes a reasonable option for multi-storey buildings.

2.2.1 Materials

LVL (Laminated Veneer Lumber)

Laminated veneer lumber, also called LVL, is an engineered wood product that uses multiple thin layers called veneers assembled with adhesives. In most of laminated veneer lumber products, the grain orientation of each layer is aligned parallel to the longitudinal direction of the member. It offers several advantages over typical lumber: it is stronger, straighter and more uniform. There are different types of LVL, which specific names and properties are manufacturer dependent.

The manufacturing process to obtain Kerto consists:
1- Sawing
2- Rotary peeling
3- Clipping
4- Drying
5- Gluing
6- Layup
7- Hot press
8- Cross – cutting
9- Rip-sawing
10- Despatching

Figure 3.5. Laminated veneer lumber manufacture [5]

LVL used for system trä8 is called KERTO® manufactured by Finnforest, can be used in all construction jobs, from new buildings to remodelling and repair. There are 3 available types of Kerto on the market: Kerto-S, Kerto-Q and Kerto-T, the first two found their applications in the system.

One of the main characteristics of Kerto-S is that the grains run longitudinally trough all the layers and this confers the strength, dimensional precision and stability which are necessary/advantageous features for beam type elements with long span lengths. In Kerto-Q approximately 20% of the veneers are glued crosswise and this permits to improve the lateral bending strength and stiffness of the panel (board/panel type elements). Moreover, the alternation of the veneers increases the dimensional stability against moisture induced changes. [5]

Kerto is at present used in trä8 for construction of roof elements, ribbed floor panels and sheathing of the stabilising wall elements.
Glued laminated timber (glulam)

Glued laminated timber, also called glulam, is a type of structural timber product composed of several layers of dimensioned timber (lamellas) glued together. Glulam has greater strength and stiffness than structural lumber of corresponding dimensions. In comparison with steel and concrete, glulam has much higher strength to weight ratio, therefore it is considered a light structural material.

The history of glulam is longer than other engineered wood products. A German patent issued in 1906 – Hetzer Binder – was the real start of modern glulam technology. Since the beginning of the 20th century, glulam has been used in a high percentage of different structures in Nordic countries. There are at least ten established glulam factories today. The manufacturing standards in the different countries are virtually identical due to a comprehensive cooperation between the building authorities. The coordination is organized and supervised by a common organization and, as a result, glulam from the Nordic countries is marked in the same way: with the “L-mark”. [7]

The manufacture process for obtain glulam consists:

1- Sawn timber is dried (12%) and sorted by its strength.
2- The layers are glued between them and planed.
3- Pressing of the layers (with a mechanical press or high frequency press).
4- Finished. The glulam can be processed, e.g. brushed, and finally it is package for the transport.
In system träδ glulam is utilised for the main load bearing elements (beams and columns), as well as for the skeleton of the stabilising elements.

2.2.2 Concept

This structural concept of system träδ is based on a modular frame of beams and columns connected in theoretically hinged/pinned manner that require an additional stabilising system. In this case, the stabilising system consists of prefabricated walls built of a glulam skeleton with Kerto-Q boards screwed and glued onto its both sides. As a result, no load bearing inner or outer walls are necessary, which enables the use of large glass areas in the façade and constitution of large open inner spaces, usually required in commercial and office buildings.
2.3 Common challenges related to timber structures

One of the most usual and logical complications for timber structures is the fire. Normally, buildings without protection against fire are highly vulnerable to them if not quickly detected and suppressed. Buildings utilizing light frame timber members are more vulnerable than heavy timber structures, since members with large cross-section withstand fire load longer. However, timber is not only combustible construction material, e.g. steel connectors and some insulating materials have also low durability to fire loads. Principally, timber buildings have burnt in the past due to the lack of effective fire compartments for containing it, fire detection systems and fast suppression methods and acceptable fire-fighting technologies, i.e. entire lack of fire protection. Nowadays, modern timber buildings are protected with non-combustible sheathing materials or by themselves, because large timber members do not burn easily due to its poor heat conductivity and protective charcoal layers that form on members during burning. This charcoal is an effective obstructor of rapid collapses of timber systems.

On the other hand, the most significant influence with respect to the physical and biological properties of timber products is moisture. Changes of the moisture content in the air cause changes of dimensions of timber members, distortion of their form, curvature, twisting, etc. Fungi and insects can be a consequence of high moisture content too. Fast changes of moisture content generate fissures which are ideal places for insects to lay their eggs and constantly high moisture content (more than 25% for a long time, i.e. weeks, is considerate as critical) can lead to discoloration of the wood and destruction by fungi [11].

However, it is worth to emphasise that not only timber can be the weak link in timber structures. For instance, during fire, steel parts that are often used to make inter-member connections are normally extremely vulnerable due to their good heat conductivity which causes lost of strength and excessively deform during fires inducing systemic collapses. On the other hand, exposed to moist conditions, steel can corrode if not protected.

As a result of its light weight, compared with concrete and steel, timber does not have enough mass to provide the necessary stabilization for a building. This could be a considerable problem when horizontal forces as wind loads act on a multi-storey structure.
and cause large deformations which can be a significant inconvenience for the inhabitants or users. In taller buildings a few structural solutions can be applied.

Normally, the lateral forces are transferred from roof systems, walls and floor diaphragms into the foundations via a system of effective connection system, i.e. multi-layered timber panels instead of nailed or screwed sheathing boards. Another alternative is to use the stair cases or elevator shafts, usually made with concrete, as a stabilization system, but this mixture of materials could create problems due to differential settlements in the materials.

Figure 3.10. Stabilization of (a) Post and Beam system (b) Big or large frame system and (c) Light frame system

One characteristic of the beam and post system is that it has hinged connections between the load bearing elements and for resisting the horizontal loads it is necessary to include an additional stabilisation structure in the building (Figure 3.10 (a)). In another system called big frame is not necessary to include an additional stabilising since the big frame has rigid joints between members that allow resisting the lateral loads (Figure 3.10 (b)). In the light frame system the timer frame together with the sheathing create so-called shear walls (Figure 3.10 (c)) which have the same function that the rigid joint in the big frame system.

In volumetric system each module is in an independent structural unit, hence they are self-stabilising and do not depend on the other volumes. This is a good characteristic
since the building can be modified without affecting other parts of it. The loads are carried mainly by the walls: the studs carry the vertical loads and connected with the sheathing, e.g. OSB or plywood, they resist the horizontal loads (Figure 3.11). These loads go from the façade to the floor and they are distributed to the inner walls. To assure the stabilisation of the whole building, the connections between modules must be strong enough to provide satisfactory transfer of shear forces. Moreover, an anchorage to the foundation has to be designed in order to prevent the uplift of the structure.

Figure 3.11. Horizontal and vertical load distribution in volumetric system

In the post and beam system, specifically in trä8, the stabilisation has to be very strong and reliable. The main challenge is that this system is planned to be used in non-residential buildings, with large spans, and because of that the use of shear walls or diagonal bracing is limited because of aesthetical reasons. The stabilising system for the building consists of prefabricated walls built of glulam skeleton with LVL boards glued and screwed onto its both sides. The elements produced in this way will have a large lateral load-carrying capacity and stiffness, and can easily stabilise a four-storey building. From these elements, the loads are transferred to the floors (diaphragm) which due to their stiff ribbed structure will transfer the horizontal loads to the beams. Although, the anchorage system and the connection between elements are under development [9], they will be designed as stiff and strong connectors.
Figure 3.12. Horizontal and vertical load distribution in trä8 system
3 PRE-ANALYSIS AND PRE-DESIGN

In this part, simplifications and equations used for the hand calculation are explained. Later, the actions are calculated (see Appendix I) and the results of this introductory analysis are interpreted for design an initial model of the building.

3.1 Analysed structure

The analysed building is based on a standard object by Moelven Byggmodul AB. The basic structure is a three-storey residential building for constructed with the volumetric module system. The project consists of two buildings with the same structure which includes 48 dwellings with total 3000 m² of living area. The aim of the thesis is to add two bottom floors to the building using trä8 system, developed by Moelven Töreboda. Due to the symmetry of the building only half of the structure is analysed, Figure 4.1. The building is located in Svedmyra, a district of Stockholm.

Figure 4.1. Partial plan of the designed building

Figure 4.2. Designed building with annexes
3.2 Initial considerations

Before starting with the hand calculations some considerations have to be taken into account in order to simplify the structure. First at all the internal walls of the volumes which are used to separate rooms have been neglected because they are not important from a structural point of view, i.e., they do not carry any load. Secondly, the vertical loads, which normally are carried by the studs, have been applied directly in the wall and because of that it is not necessary to draw the studs. Finally, to calculate the wind actions, the shape of the building was simplified to rectangular, Figures 5.1 and 5.2.

![Figure 5.1. Schema of the general shape of the building (top view)](image1)

![Figure 5.2. Schema general of the simplified shape of the building](image2)

3.3 Actions on the building

There are two kinds of natural actions that have to be taken into consideration during the design of this building: snow and wind. They depend of the geographical location of the building. These actions are calculated according the Eurocode and the respective National Annex. The detailed calculations for determining these loads can be found in the Appendix 1, and the final values are presented below.
Snow: 1,66 kN/m²

Wind:

<table>
<thead>
<tr>
<th>ROOF</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta = 0^\circ ) (wind)</td>
<td>( w_i ) (kN/m²)</td>
<td>-1,24</td>
<td>-1,11</td>
<td>-0,41</td>
<td>-0,55</td>
</tr>
<tr>
<td></td>
<td>( w_e ) (kN/m²)</td>
<td>-1,12</td>
<td>-1,00</td>
<td>-0,37</td>
<td>-0,50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta = 90^\circ ) (wind)</td>
<td>( w_i ) (kN/m²)</td>
<td>-1,80</td>
<td>-1,80</td>
<td>-0,83</td>
<td>-0,69</td>
</tr>
<tr>
<td></td>
<td>( w_e ) (kN/m²)</td>
<td>-1,62</td>
<td>-1,62</td>
<td>-0,75</td>
<td>-0,62</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FAÇADE</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>First case</td>
<td>( w_i ) (kN/m²)</td>
<td>-1,66</td>
<td>-1,11</td>
<td>-</td>
<td>1,11</td>
</tr>
<tr>
<td></td>
<td>( w_e ) (kN/m²)</td>
<td>-1,49</td>
<td>-1,00</td>
<td>-</td>
<td>1,00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Second case</td>
<td>( w_i ) (kN/m²)</td>
<td>-1,66</td>
<td>-1,11</td>
<td>-0,69</td>
<td>1,11</td>
</tr>
<tr>
<td></td>
<td>( w_e ) (kN/m²)</td>
<td>-1,49</td>
<td>-1,00</td>
<td>-0,62</td>
<td>1,00</td>
</tr>
</tbody>
</table>

Another load that needs to be taken into consideration is the dead load of the building.

For the volumetric system the dead loads are:

<table>
<thead>
<tr>
<th>LOAD</th>
<th>kN/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g_{SVV} ) (outside wall)</td>
<td>0,531</td>
</tr>
<tr>
<td>( g_{KLXV} ) (wall between modules)</td>
<td>0,296</td>
</tr>
<tr>
<td>( g_{ARJ} ) (floor)</td>
<td>0,517</td>
</tr>
<tr>
<td>( g_{MN} ) (ceiling)</td>
<td>0,296</td>
</tr>
<tr>
<td>( g_{AVY} ) (roof)</td>
<td>0,285</td>
</tr>
<tr>
<td>( n_d ) (furniture)</td>
<td>0,5</td>
</tr>
</tbody>
</table>

For the trä8 system the self weight of the floor and the beams and columns are:

<table>
<thead>
<tr>
<th>LOAD</th>
<th>kN/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor</td>
<td>0,39</td>
</tr>
<tr>
<td>Beam</td>
<td>0,01·section-length</td>
</tr>
<tr>
<td>Column</td>
<td>20,19·section-length</td>
</tr>
</tbody>
</table>

19
3.4 Load combinations (according to Eurocode)

All the calculations have been made for the ultimate limit state (ULS), which considers safety of the people and of the structure. Moreover, the protection of the contents supported by the structure can be added in these states. The relevant ULSs for the timber structure that have to be considered are:

- Loss of equilibrium of part or all the structure
- Failure by excessive deformation
- Failure as a mechanism
- Failure due to rupture
- Failure due to loss of stability

For the calculation of these states it is necessary to decide which load combinations are going to be used. Afterwards, the most unfavourable of these cases is chosen and applied to the building to design the columns and beams of the träå system. There are three types of actions that are included in the combinations:

1. Permanent actions (G): Actions that are applied always at the building and have a negligible variation in the time, e.g. dead loads.

2. Variable actions (Q): Actions that have a notable variation in the time, e.g. snow and wind.

3. Accidental actions (A): Actions that apply an instant load, during a short period of time, e.g. explosion or impacts.

From these, only 2 actions, permanent and variable are going to be used in the design of this building.

According to the Eurocode, the following load combinations have to be considered:

\[ \sum_{i=1}^{n} y_{G_j} G_{kj} + y_{Q_1} Q_{k1} + \sum_{i>1} y_{Q_i} \psi_{Q_i} Q_{ki} \]  \hspace{1cm} (5.1)

Where \( G_{ij} \) are the permanent actions, \( Q_{k1} \) is the dominant variable action and \( Q_{ki} \) are the other variable actions. The coefficient \( \gamma \) in front of each action is the safety factor and the \( \psi \) represents the reduction factor. These values are given by the Eurocode and are defined as follows:
Another important load factor that has to be used during design for the security is $k_{mod}$, which refers to the service class and the load duration class. The first one depends on the moisture content of the wood and is divided into 3 groups:

a) Service class 1 – where the average moisture content in most softwoods will not exceed 12%,

b) Service class 2 – where the average moisture content in most softwoods will not exceed 20%.

c) Service class 3 – where the average moisture content in most softwoods exceeds 20%.

The load duration class illustrates the loss of the strength properties of the timber and the longer the duration of the load, the greater the reduction is going to be.

Taking into account the service class and the load duration class, it is possible to determine the value of $k_{mod}$ (Table 5.7) and determine the load combinations (Table 5.8). Finally, the combinations for ultimate limit state are obtained (Table 5.9)
### Table 5.7. Values of $k_{mod}$ regarding service class and load duration class

<table>
<thead>
<tr>
<th>Material</th>
<th>Service Class</th>
<th>Permanent</th>
<th>Long term</th>
<th>Medium term</th>
<th>Short term</th>
<th>Instantaneous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glulam</td>
<td>2</td>
<td>0,60</td>
<td>0,70</td>
<td>0,80</td>
<td>0,90</td>
<td>1,10</td>
</tr>
<tr>
<td>LVL</td>
<td>3</td>
<td>0,50</td>
<td>0,55</td>
<td>0,65</td>
<td>0,70</td>
<td>0,90</td>
</tr>
</tbody>
</table>

### Table 5.8. Loads applied over the building

<table>
<thead>
<tr>
<th>Loads</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self weight</td>
<td>Roof, ceiling, floor, furniture, walls</td>
<td>All the dead loads of the building ($s_o$)</td>
</tr>
<tr>
<td>Snow</td>
<td>Snow 1, snow 2</td>
<td>Snow 1: Equal load over both side of the roof ($s_1$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Snow 2: Different load in each side of the roof ($s_2$)</td>
</tr>
<tr>
<td>Wind roof</td>
<td>Wind 1, wind 2</td>
<td>Wind 1: Direction 0°, only possible to combine with wind 4 ($w_1$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wind 2: Direction 90°, only possible to combine with wind 3 ($w_3$)</td>
</tr>
<tr>
<td>Wind façade</td>
<td>Wind 3, wind 4</td>
<td>Wind 3: Perpendicular to the shortest façade, only possible to combine with wind 2 ($w_3$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wind 4: Perpendicular to the largest façade, only possible to combine with wind 1 ($w_4$)</td>
</tr>
</tbody>
</table>

### Table 5.9. Load combinations applied

<table>
<thead>
<tr>
<th>ULS 1</th>
<th>$1,5 \cdot s_1 + 1,35 \cdot s_w + 0,75 \cdot (w_1 + w_4)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULS 2</td>
<td>$1,5 \cdot s_1 + 1,35 \cdot s_w + 0,75 \cdot (w_2 + w_3)$</td>
</tr>
<tr>
<td>ULS 3</td>
<td>$1,5 \cdot s_2 + 1,35 \cdot s_w + 0,75 \cdot (w_1 + w_4)$</td>
</tr>
<tr>
<td>ULS 4</td>
<td>$1,5 \cdot s_2 + 1,35 \cdot s_w + 0,75 \cdot (w_2 + w_3)$</td>
</tr>
<tr>
<td>ULS 5</td>
<td>$0,75 \cdot s_1 + 1,35 \cdot s_w + 1,5 \cdot (w_1 + w_4)$</td>
</tr>
<tr>
<td>ULS 6</td>
<td>$0,75 \cdot s_1 + 1,35 \cdot s_w + 1,5 \cdot (w_2 + w_3)$</td>
</tr>
<tr>
<td>ULS 7</td>
<td>$0,75 \cdot s_2 + 1,35 \cdot s_w + 1,5 \cdot (w_1 + w_4)$</td>
</tr>
<tr>
<td>ULS 8</td>
<td>$0,75 \cdot s_2 + 1,35 \cdot s_w + 1,5 \cdot (w_2 + w_3)$</td>
</tr>
</tbody>
</table>
3.5 Calculation of the loads

The calculations have been realized using a simplified method that permits, firstly, to calculate the distribution of the loads in the volumetric system and, later, to transfer these loads from the tróδ system to the foundations. The complete results and the procedure can be found in the Appendix 2. Here the results for the whole volumetric system are presented.

Complete volumetric system, i. e., the 3 storeys:

![Figure 5.3 Top view of the building](image)

For each module the walls are distributed as showed in Fig. 5.4.

![Figure 5.4 Designation of the walls in a module](image)
Table 5.10 Values for the complete structure of volume system. Hand calculation.

**Hand Calculation (everything in kN/m)**

<table>
<thead>
<tr>
<th>Module</th>
<th>Wall 1</th>
<th>Wall 2</th>
<th>Wall 3</th>
<th>Wall 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12,40</td>
<td>11,16</td>
<td>12,40</td>
<td>21,10</td>
</tr>
<tr>
<td>2</td>
<td>12,40</td>
<td>21,10</td>
<td>12,40</td>
<td>22,59</td>
</tr>
<tr>
<td>3</td>
<td>13,84</td>
<td>12,79</td>
<td>23,04(^1)</td>
<td>13,84</td>
</tr>
<tr>
<td>4</td>
<td>13,84</td>
<td>23,36</td>
<td>13,84</td>
<td>12,79</td>
</tr>
<tr>
<td>5</td>
<td>12,40</td>
<td>22,59</td>
<td>12,40</td>
<td>21,10</td>
</tr>
<tr>
<td>6</td>
<td>12,40</td>
<td>21,10</td>
<td>12,40</td>
<td>22,73</td>
</tr>
<tr>
<td>7</td>
<td>12,40</td>
<td>22,73</td>
<td>12,40</td>
<td>22,73</td>
</tr>
<tr>
<td>8</td>
<td>12,40</td>
<td>22,73</td>
<td>12,40</td>
<td>22,59</td>
</tr>
<tr>
<td>9</td>
<td>13,84</td>
<td>12,79</td>
<td>23,04(^1)</td>
<td>13,84</td>
</tr>
<tr>
<td>10</td>
<td>13,84</td>
<td>23,36</td>
<td>13,84</td>
<td>12,79</td>
</tr>
<tr>
<td>11</td>
<td>12,40</td>
<td>22,59</td>
<td>12,40</td>
<td>21,10</td>
</tr>
<tr>
<td>12</td>
<td>12,40</td>
<td>21,10</td>
<td>12,40</td>
<td>11,16</td>
</tr>
</tbody>
</table>

\(^1\) This wall has two values because one of them corresponds to the wall that excels the building
4 COMPUTER ANALYSIS

In this part, the software used for the computer calculations as well as the methodology utilised by this program are described.

4.1 Finite element method

The beginning of this method can be placed on 1940’s, specifically, in 1941 and 1942 when Alexander Hrennikoff and Richard Courant shared an essential element in their work: a mesh. Finite element method (FEM) is general used for solve complicated elasticity and structural problems in civil and aeronautical engineering [22]. The method is a numerical technique for finding accurate solutions of partial differential equations as well as of integral equations. The main characteristic of the mesh is that it is composed of elements which have physical properties like thickness, coefficient of thermal expansion, density, Young’s modulus, shear modulus and Poisson’s ratio. These elements are interconnected by nodes which are characterized by displacement vectors or degrees of freedom that include translations and rotations. When this nodes move, they drag the elements along in the way dictated by the element formulation and because of that the displacements of any points in the element are interpolated from the nodal movements. Thus an approximated solution can be found.

4.2 FEM Design

The program used for the numerical analysis is called FEM Design and is distributed by StruSoft. This software uses finite element method to analyze the problems and to obtain solutions, and it is composed of different modules: plate, wall, plane strain, 3D frame, 3D structure and reinforcement (only for concrete problems). The three firsts are used to analyze simple elements, e.g. floors, and the last ones are to study cases where it is needed to evaluate 3D elements that cannot be considered as flat elements with a constant thickness. As in this case the analyzed structure is a multi-storey building, thus the 3D structure module is used which to make an accurate study of this type of construction [23].

4.3 Analysis point

The designed building has two first storeys built with trä3 system and three following storeys made with volumetric module system. The interesting point is the connection between systems because the way of distributing and transferring loads for both systems is different. Firstly, it was attempted to design the building without stabilising walls and in next step the stabilising walls were added to satisfy the resistance demand against the horizontal loads.
4.4 Analysis of the pre-models

Before making the model of the whole building, 5 models of the volumetric system have been realized to check if the connections between the different modules distribute the vertical loads in the correct way. Later horizontal loads have been compared too but only have been necessary to analyze a simplification of one façade due to the behaviour of all the others façades is the same.

Different simplifications have been taken in consideration:

1. The walls have been simplified to solid timber but with the characteristics of the normal walls for volumetric system since it would be too complicated to analyse the reactions in all the studs.

2. Short exterior walls have no connection between the ceiling and the other walls of the volumetric system. They are nearly independent.

3. Self weight of the walls has been considered as a line load on each wall.

For realization of the pre-models the following tools have been used:

- Wall: It permits to define a wall using only two reference points.

- Plate: It permits to define a plate using only two reference points.

- Line support group: It permits to define the connection between the walls and the soil.

- Line-Line connection: It permits to define a connection between two lines.

In the first stage of analysis, the horizontal loads were checked.

4.4.1 Horizontal loads

ONE MODULE

Firstly, one module has been designed to check the connections between the ceiling and the walls of it.
To design a module, 4 walls and a ceiling have been defined and connected (Fig. 6.1). The predefined connection between them has been hinged. However, as the walls between modules (longest walls) carry different loads than the exterior walls (shortest walls), the joint has been changed to “no connection” with the line-line connection and, hence, there is no relation between the 4 walls.

After defining the structure, the loads were applied. Three different types of vertical loads have been used: wind, snow and self weight (of the walls, ceiling and roof and service).

Figure 6.1. Structure of 1 module

Figure 6.2. Snow and dead loads respectively
Once the loads have been applied, the mesh was defined. For this purpose the automatic mesh design was used.

Figure 6.3. One module meshed

Finally, the software performed the calculation and gave the results.

Figure 6.4. Lineal and original reactions distribution of one module

FEM-Design gave two different results: lineal and original reaction distribution. The lineal distribution consists in an average of the real results which are the ones of the original distribution. Normally, as the results in a Finite Method Element program depend
on the mesh, the values given in the lineal distribution are the most approximate to the hand calculation.

The results of analysis of each pre-model can be found in the Appendix 2.

TWO MODULES

The design has been realised in the analogous was as for a single module. Consequently, here and in the other two following points, the results obtained in FEM-Design are presented.

Figure 6.5. Lineal reactions distribution and original reactions distribution of two modules
As it can be observed in the Figure 6.6, the wall between modules 3 and 4 is carrying a considerable load, but in order to simplify the model in the further analysis, it was
assumed that the module 3 and 4 are only one module, and the load carried by the eliminated wall was distributed on the long walls of this module 3-4.

HALF OF THE FIRST STOREY OF VOLUMETRIC SYSTEM

Figure 6.8. Lineal reactions distribution and original reactions distribution of half of the first storey

Figure 6.9. Module numeration
4.4.2 Vertical loads

First, a vertical element wall with the measures of one of the building façades has been made in FEM-Design, this means that one three-storeys façade has been simplified in one element and any connection have been used, only one simple element. In this wall has been applied the wind load which is applied in the façade of the building.
The wind load is transferred to the bottom of the wall as a lineal load. This line load is equivalent to the pressure created by the wind.

### 4.5 Comparison of the results of the pre-models

To control if the calculations made in FEM-Design give the expected results, the reactions on the walls were analysed and compared with the hand calculation. For this comparison the equation used is:

\[
\%\theta = \frac{R_{\text{theoretical}} - R_{\text{fem}}}{R_{\text{fem}}} \cdot 100
\]  

(6.1)

With (6.1) the error among the hand calculations results and the FEM-design results can be calculated and it is possible to decide if the load distribution provided by the software behaves like the theoretical distribution.

#### 4.5.1 Horizontal loads

<table>
<thead>
<tr>
<th></th>
<th>Error lineal distribution (%)</th>
<th>Error original distribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long exterior walls</td>
<td>2,95</td>
<td>17,22</td>
</tr>
<tr>
<td>Short exterior walls</td>
<td>-5,56</td>
<td>5,48</td>
</tr>
</tbody>
</table>
As it can be observed, the error in the original distribution is bigger if it is compare with the error in the linear distribution. This is due to the fact that the real distribution of the loads is not completely homogeneous and the hand calculation ignores it and makes a linear approximation. Due to this the error between hand calculation and linear distribution is less. However, only with one module it is impossible to confirm this because only two different values can be analysed, hence, in the next comparison the original distribution was considered too.

*Table 6.2. Comparison between FEM-Design and hand calculation for 4 modules*

<table>
<thead>
<tr>
<th>Module</th>
<th>Wall</th>
<th>Error lineal distribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Long exterior wall</td>
<td>2,81</td>
</tr>
<tr>
<td>1-2</td>
<td>Wall between modules</td>
<td>-11,05</td>
</tr>
<tr>
<td>1 and 2</td>
<td>Short exterior wall (Top)</td>
<td>24,08</td>
</tr>
<tr>
<td>1 and 2</td>
<td>Short exterior wall (Bottom)</td>
<td>15,67</td>
</tr>
<tr>
<td>2-3</td>
<td>Wall between modules</td>
<td>0,36</td>
</tr>
<tr>
<td>2-4</td>
<td>Wall between modules</td>
<td>0,72</td>
</tr>
<tr>
<td>3</td>
<td>Short exterior wall, module 2 side</td>
<td>16,79</td>
</tr>
<tr>
<td>3-4</td>
<td>Transversal wall</td>
<td>13,26</td>
</tr>
<tr>
<td>3</td>
<td>Short exterior wall</td>
<td>19,12</td>
</tr>
<tr>
<td>3</td>
<td>Long exterior wall</td>
<td>0,87</td>
</tr>
<tr>
<td>4</td>
<td>Short exterior wall</td>
<td>58,63</td>
</tr>
<tr>
<td>4</td>
<td>Long exterior wall</td>
<td>2,49</td>
</tr>
</tbody>
</table>

The only remarkable thing in the table 6.3 is the 58,63% of error in one of the exterior walls. In Table 6.3 it can be observed that this big error has disappeared and because of that it is not going to be taken into consideration. However, it was important to find an explanation for this anomaly. One explanation for this huge difference could be that FEM-Design provides an average value for the lineal distribution and in every wall connection the load result has a peak of value which increases the load distribution of each wall. In the second case volume 4 is not the last one and has volume 5 next to it what makes that peak value in this connection is minor due to the distribution of the loads is hold by two different walls of two different modules. Another explanation is that it is
difficult to refine the mesh next to the connections and it is possible that this peak of value is bigger in the first case because of a non accurate mesh between walls. Finally, the values for the completely building is going to be exposed, but firstly for the error of whole building first is necessary to define which is the name of every wall in the modules:

![Figure 6.12. Distribution of the walls on each module](image)

Every module was divided into four walls except the ones that excels the building. In this case, the walls that are longer than the other ones have been divided into two parts, i.e., in two different walls as can be observed in the following tables. In Fig. 6.13 the division into modules is presented.

![Figure 6.13. Schema of all the modules](image)
Table 6.3. Comparison between FEM-Design lineal distribution and hand calculation for the whole building

<table>
<thead>
<tr>
<th>Module</th>
<th>Wall 1</th>
<th>Wall 2</th>
<th>Wall 3</th>
<th>Wall 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16,42</td>
<td>13,98</td>
<td>26,49</td>
<td>-15,89</td>
</tr>
<tr>
<td>2</td>
<td>16,42</td>
<td>-15,89</td>
<td>26,49</td>
<td>-11,71</td>
</tr>
<tr>
<td>3</td>
<td>10,67</td>
<td>30,69</td>
<td>-13,45</td>
<td>13,34</td>
</tr>
<tr>
<td>4</td>
<td>10,67</td>
<td>-11,58</td>
<td>13,34</td>
<td>34,44</td>
</tr>
<tr>
<td>5</td>
<td>28,75</td>
<td>-11,05</td>
<td>26,49</td>
<td>-8,78</td>
</tr>
<tr>
<td>6</td>
<td>28,75</td>
<td>-8,78</td>
<td>26,49</td>
<td>-13,67</td>
</tr>
<tr>
<td>7</td>
<td>28,75</td>
<td>-13,67</td>
<td>26,49</td>
<td>-14,82</td>
</tr>
<tr>
<td>8</td>
<td>28,75</td>
<td>-14,82</td>
<td>26,49</td>
<td>-11,67</td>
</tr>
<tr>
<td>9</td>
<td>10,45</td>
<td>33,43</td>
<td>-13,41</td>
<td>13,34</td>
</tr>
<tr>
<td>10</td>
<td>10,45</td>
<td>-11,88</td>
<td>13,34</td>
<td>32,96</td>
</tr>
<tr>
<td>11</td>
<td>17,22</td>
<td>-12,69</td>
<td>26,49</td>
<td>-15,79</td>
</tr>
<tr>
<td>12</td>
<td>17,22</td>
<td>-15,79</td>
<td>26,49</td>
<td>13,35</td>
</tr>
</tbody>
</table>

4.5.2 Vetical loads

Table 6.4. Error of FEM-Design in vertical loads respect the handmade calculation

<table>
<thead>
<tr>
<th>Lineal distribution error (%)</th>
<th>Original distribution error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,02</td>
<td>41,42</td>
</tr>
</tbody>
</table>

As visible in Table 6.4, the error for the lineal distribution is smaller than the one of the original distribution. This fact permits confirm that the hand calculations for vertical loads are a simplification of the real distribution and it does not consider the possible disturbances that the joints with another walls can create.

4.5.3 Considerations for building design

Finally, after see that the distribution which is more similar to the hand calculations is the lineal, it is possible to have some conclusions for design the building:

1. Hand calculations have a high error in the values due to they do not considerate that the walls of each module are not completely independent.

\(^2\) This wall has two values because one of them corresponds to the wall that excels the building.
from the other ones and because of that some reactions have been incremented and another ones have been decreased its value.

2. Some of the errors are higher than 20 % but the high reactions have a negative error, i.e., the hand calculations have a bigger value and, hence more security coefficient if the design is based in the maximum reaction.

3. Although, in theory the snow load is carried only for the short exterior walls and the self weight of the roof for the long exterior walls, actually, all the walls carry part of every single load in major or minor measure because the ceiling is supported for the 4 walls.

4. For design the columns and beams of the trä8 system is going to be used the reactions given by FEM-Design because they follow the most realistic distribution, although it can be said that the values given by the hand calculation can be used for design too because the biggest values have the hugest error but in a security direction.

5. Due to the software does not make difference between a wall and a façade, the wind load in the trä8 system is going to be distribute at the columns and the stabilisation walls, without considerate the façades in this part of the building.
5 BUILDING DESIGN

The main part of the project is performed in this section. This consists in the final design of the columns and beams distribution for the trä8 system.

5.1 Eurocode 5

Eurocode 5 is the normative for timber structures inside of the European frame. This rules permit to design constructions from the safety point of view. In this Master’s Thesis the Eurocode 5 had been used for design the columns and beams of the trä8 system. For this purpose the following possible failures had been checked:

1- Combined bending and axial compression

\[ \sigma_{c,0,d} \leq f_{c,0,d} \]  
\[ \left( \frac{\sigma_{c,0,d}}{f_{c,0,d}} \right)^2 + \frac{\sigma_{m,1,d}}{f_{m,1,d}} + k_m \cdot \frac{\sigma_{m,2,d}}{f_{m,2,d}} \]  
\[ \left( \frac{\sigma_{c,0,d}}{f_{c,0,d}} \right)^2 + k_m \cdot \frac{\sigma_{m,1,d}}{f_{m,1,d}} + \frac{\sigma_{m,2,d}}{f_{m,2,d}} \]

where

\( \sigma_{c,0,d} \) is the design compressive stress parallel to the grain

\( f_{c,0,d} \) is the design compressive strength parallel to the grain

\( \sigma_{m,1,d} \) is the design bending stress about the principal 1-axis

\( f_{m,1,d} \) is the design strength about the principal 1-axis

\( \sigma_{m,2,d} \) is the design bending stress about the principal 2-axis

\( f_{m,2,d} \) is the design strength about the principal 2-axis

\( k_m \) is the factor for the redistribution of bending stresses in a cross-section
2- Combined shear and torsion

\[
\frac{V \cdot a}{2a_t} = \tau_d \leq f_{v,d}
\]  

(7.4)

where

- \(f_{v,d}\) is the design shear strength
- \(\tau_d\) is the design shear stress

3- Flexural buckling around axis 1

\[
\beta_c = 0.1
\]  

(7.5)

\[
\lambda_1 = \frac{l_e}{a/\sqrt{12}}
\]  

(7.6)

\[
\lambda_{rel,1} = \frac{\lambda_1}{\pi} \sqrt{\frac{f_{c,0.k}}{E_{0.05}}}
\]  

(7.7)

\[
k_1 = 0.5 \cdot \left(1 + \beta_c \cdot (\lambda_{rel,1} - 0.3) + (\lambda_{rel,1})^2\right)
\]  

(7.8)

\[
k_{c,1} = \frac{1}{1 + \sqrt{k_1^2 - \lambda_{rel,1}^2}}
\]  

(7.9)

\[
\frac{\sigma_{c,0,d}}{k_{c,1} f_{c,0,d}} + \frac{\sigma_{m,1,d}}{f_{m,1,d}} + k_m \frac{\sigma_{m,2,d}}{f_{m,2,d}}
\]  

(7.10)

where

- \(\beta_c\) is the straightness factor
- \(\lambda_1\) is the slenderness ratio corresponding to bending about the 1-axis
- \(l_e\) is the effective length
- \(\lambda_{rel,1}\) is the relative slenderness ratio corresponding to bending about the y-axis
- \(f_{c,0,k}\) is the characteristic compressive strength along the grain
$E_{0.05}$ is the fifth percentile (characteristic value) of modulus of elasticity

$k_{c,1}$ is the instability factor

4- Flexural buckling around axis 2

\[ \beta_c = 0.1 \]  \hspace{2cm} (7.5)

\[ \lambda_2 = \frac{L_c}{a \sqrt{\pi^2}} \]  \hspace{2cm} (7.11)

\[ \lambda_{rel,2} = \frac{\lambda_1}{\pi} \sqrt{\frac{f_{c,0.05}}{E_{0.05}}} \]  \hspace{2cm} (7.12)

\[ k_2 = 0.5 \cdot \left( 1 + \beta_c \cdot (\lambda_{rel,2} - 0.3) + (\lambda_{rel,2})^2 \right) \]  \hspace{2cm} (7.13)

\[ k_{c,2} = \frac{1}{1 + \frac{\sqrt{k_2^2 - k_{rel,2}^2}}{k_{c,2}}} \]  \hspace{2cm} (7.14)

\[ \frac{\sigma_{c,0,d}}{k_{c,2} f_{c,0,d}} + k_m \cdot \frac{\sigma_{m,1,d}}{f_{m,1,d}} + \frac{\sigma_{m,2,d}}{f_{m,2,d}} \]  \hspace{2cm} (7.15)

The explanation of every factor could be found in the flexural buckling around axis 1.

Since the columns in the analysed building are subjected to compression, their buckling lengths need to be defined. The columns are continuous, but the effective length is a half of the column ($L_c=2.5$ m) The top part of the column is assumed to have pinned connections between the floors so its buckling length is 1.0 L_c. The bottom part of the column is pinned at the top and fixed to the foundation, so its buckling length is equal 0.7L_c. (Fig. 7.1)
These equations have been applied for the most unfavourable load combination, ULS 7, and for the most loaded beam and column.
5.2 Preliminary assumptions for trä8 system

To be able to perform the analysis in the software FEM Design, that uses only simple elements and definition of composite section of the stabilising wall made of two different wood-based materials is not possible, the substitute solid element was created.

The material properties (the stiffness) were chosen for the substitute section, so the elastic deformation of the cantilever beam is equal of the deflection of the real stabilising wall and the elastic deformation of a simple supported beam is equal of the real deflection of the floor:

![Diagram](image)

Figure 7.3. Original profile and substitute for stabilisation wall and floor

<table>
<thead>
<tr>
<th></th>
<th>$E$ (N/mm²)</th>
<th>$E_{0.05}$ (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stabilisation wall</td>
<td>8846,60</td>
<td>8042,37</td>
</tr>
<tr>
<td>Floor</td>
<td>9440</td>
<td>8581,82</td>
</tr>
</tbody>
</table>

Table 7.1. Modulus of Elasticity of the trä8 stabilization wall and floor

The calculation of the values can be found in the Appendix 3.

5.3 FEM Design procedure

The most important part design of trä8 system is that the columns and beams have to support the Ultimate Limit States (ULS). The load combinations designed and the equations that have to be checked are according to this concept.

FEM Design has a timber module that permits to design beams and columns according to the Eurocode and the following procedure has been used:
1. Analysis of the building.

2. Selection of the buckling length for columns and beams. In this case the value is 1 as has been explained in the chapter 7.1.

3. Design parameters calculations have to be checked.

4. Selection of the section that are going to be reviewed. In this case the sections were recommended to have to the width of 215 mm in order to optimize the design (thickness of stabilising walls is 214 mm and is unlikely be changed).

5. Automatic design of the columns and beams by the software.

After this, the program gives the minimum profile that every column or beam, needs for satisfying the requirements of Eurocode and finally the profile of the most loaded element has to be selected in order to simplify the construction of the building.

5.4 Results of FEM Design

In this part, the three different variants of design analysed with FEM Design software are presented. First is going to be considered without stabilisation walls, only with columns, later with only stabilisation walls and, finally, with an optimized distribution of stabilisation walls. An important point that has to be considered is that not always the most loaded column is the most unfavourable one due to, normally, it has the highest section what makes the column design not on the limit given by the Eurocode.

5.4.1 Building without stabilisation walls

2 options have been analysed. The first one has *trc8* floor under the volumetric system, giving more stiffness to the building and a second one without it, which reduces the maximum load of columns and beams.
All the loads for the trä8 system have been applied and distributed on the columns and beams and the loads of the volumetric system were applied as the same way as on the pre-modules.

CASE 1

The analysis of this case is the most unfavourable because the columns and the beams are large and the floor of the second floor does not have enough stiffness to avoid the high deformation of the elements. The software is incapable to find a solution for one of the beams because the maximum section (215x1350 mm) introduced in the software is not strong enough for resist the loads.
As can be observed in the figure 7.6 the element number 7, which is the most loaded in the structure for this case, does not satisfy the conditions for the shear effects that Eurocode requires. In the Appendix 4 the equations of Eurocode 5 used for design the building are exposed.

Other unacceptable point can be observed in the figure 7.5 where all the columns are yellow close to 7th floor, i.e., in the connection between the 7th floor and the columns. This means that the utilisation values of the columns in this point is between 80-100% which are not acceptable on structural engineering.

In addition to only one beam is out of the range and the utilisation of most of the columns is higher than 80%, it has to be considered, in order to design the building without
stabilisation walls, that the section of most of the elements is higher than 300 mm and this is unsatisfactory due to the fact that the building has to be the most simple possible and this include that elements must have a similar width compare with the stabilisation walls.

CASE 2

In this case a trä8 floor under the volumetric system has been applied in order to give more stiffness to the elements and try to achieve more realistic results.

![Figure 7.7 Utilisation of the elements with two floors of trä8 system](image)

**Figure 7.7 Utilisation of the elements with two floors of trä8 system**

![Figure 7.8 Summary of the utilisation of the most loaded element (B.7)](image)

**Figure 7.8 Summary of the utilisation of the most loaded element (B.7)**
Unless it could be thought that with one floor of træ8 system more the elements are going to have enough stiffness to hold the building, the solution is worse than in the previous case due to two beams does not have solution under 215 x 1350 mm. This could be because an extra floor gives more stiffness but it gives more weight too. The moment created by the wind increases its value because of the extra weight, becoming the træ8 floor in a disadvantage for the system, especially for the columns placed in opposite side of the wind.

5.4.2 Building with stabilisation walls

This case analyzes what happens when almost all the columns (only two remain) are replaced by a stabilisation wall. Unless it is known that this solution is not optimal it would be interesting to know if it is possible that the træ8 system hold the volumetric system before search an optimal distribution.
As it can be observed on the Figure 7.11, the colour of the two columns is dark green. This means that the utilisation of the columns is less than 60%, which is within the allowed by code range. Therefore it can be concluded that the stabilising walls fulfil their function and this version is viable, although is not optimal.
As can be observed in Fig. 7.13, the maximum displacement for a section of 215x180 mm is 14.65 mm which is within the recommended range (L/500).

**5.4.3 Optimization of stabilisation walls**

Finally, an optimal distribution of columns and stabilising walls was achieved, visible in Fig. 7.14.
Figure 7.14. Final design of the building

Figure 7.15. Displacements of the final building
The maximum horizontal displacement obtained for this design is 19 mm and, despite it is bigger than the limitation given by Eurocode (L/500) it is possible to used due to is still below than the extreme value (L/300) that Eurocode gives as the worst case for glulam. It is necessary to say that the utilisation of the cross-sections is less than 60%. These two aspects make this distribution an optimal solution from the displacements point of view and stresses to which the elements are subjected.
It is not possible to present in this report all the values of stresses, but the extreme values obtained are: the maximum 694.4 kN and the minimum -579.6 kN. These high stresses have to be considered when the design of the columns and stabilisation walls are made since the connection between systems is very important because each system has a different behaviour in a distribution of the loads.

*Figure 7.17 Connection stresses.*

It can be observed in the figure 7.17 that stresses in the connection between volumetric system storeys are imperceptible, i.e., they are lower than the stresses found between stabilisation walls and the last storey of volumetric system and the foundations.
6 FINAL REMARKS

Once all possibilities have been considered, the different solutions have been compared
to evaluate the behaviour of different configurations and find an optimal solution.

6.1 Conclusions from the handmade calculations

First it has to be said that the hand calculation has a relative big error compared to the
computer numbers. This could be a consequence of the small load values which and that a
small difference between results from hand calculations and FEM Design give a large
error. Another point is that in theory all the joints between walls or ceilings are not
considered because, by default, different walls are set to carry different loads, e.g., snow
load is only carried by the exterior walls. FEM Design considers the connection of
external wall to the walls between modules, which is closer to reality. As a result, the
reaction forces at the corners become a peak value that in turn increases the average value
of the lineal reaction force, leading the error in comparison to the handmade calculations.
It should be observed that, unless the errors are considerate, when the most loaded wall is
analyzed, the values attained by hand are bigger than the values attained by FEM Design.
Consequently, as buildings are designed by its most loaded wall, hand calculations
provide forces on the safe side, i.e. the obtained forces will always be higher than what
would be expected in reality.

6.2 Conclusions from the numerical analysis

The cases without stabilisation walls can be directly eliminated due to the low load-
carrying capacity of the columns and the not sufficient stiffness to resist the moment
caused by the wind load. When a stabilisation wall is used, the cross-section of beams
and columns are reduced considerably providing a much more realistic solution. In this
case, with much fewer columns, the maximum section necessary is 215x360 mm.
However, the builder is interested in columns and beams with a cross-section where the
smallest side is the maximum of the width of the stabilisation walls (215x2500 mm).
Another aspect that makes this solution not practically useful is because the point of the
trá8 system is to make large spans possible for e.g. shops. With this solution, the
stabilisation walls do not permit the use of large windows, because it is impossible to
design a hole in the stabilization walls with as they will lose their function. Consequently,
this solution is not feasible for the bottom storeys.

The last considered design is the one that gives the best characteristics. The section of the
elements is the smallest (215x180mm), the number of stabilisation walls is less than in
the previous design because some of them have a T form which optimize their use. For
design reasons, the section will be changed to 215x225 mm which results in lower
utilization of the elements. Finally it has to be commented that to understand the full behaviour of the building and the correct distribution of the loads, a more accurate model should be created as some simplifications has been made. However, the model used in this work provides a good approximation of the possible behaviour of this mix building.

6.3 General conclusions

The final design of the building is with columns and beams of 215x225 mm, similar to the width of the stabilisation walls. It has been decided to include stabilisation walls between every two alternate column allowing space for high windows giving the possibility of use the trä8 storeys as shops or offices. If it is necessary to use more windows, the stabilisation walls could be a problem but is impossible to reduce them due to the whole building will lose its stability. The use of Fem-Design has been essential in deciding the correct distribution of columns and stabilisation walls. However, the difficulty of modelling the trä8 materials diminishes the accuracy of obtained results.

6.4 Future research

After conducting this Master’s Thesis, the following recommendations can be given for the future work on joining the two systems:

- More accurate results could be achieved if the actual materials and structures of the composite elements were used. This was not possible in FEM-Design, but other more advanced software could be used.

- A thorough analysis of connections between the volumetric and the trä8 systems should be performed.

- From the proposed design of the trä8 system, an accurate analysis of connection stresses between trä8 elements could be performed and, maybe, a better design could be achieved.

- One inconvenience of this design is that is a design for a specific building. It would be interesting to create a general design suitable for different buildings.
7 REFERENCES


APPENDIX 1. ACTIONS

A1.1 Snow

All of following calculations have been realized according to Eurocode 1 (EN 1991-1-3)

Equation for calculating the snow load:

\[ s = \mu_t \cdot C_o \cdot C_t \cdot s_k \]  \hspace{1cm} (A1.1)

where

\( \mu_t \) is the snow load shape coefficient

\( s_k \) is the characteristic value of snow load on the ground

\( C_o \) is the exposure coefficient

\( C_t \) is the thermal coefficient

Firstly \( s_k \) is calculated using the following map:

![Switzerland, Finland: Snow Load at Sea Level](image)

*Figure A1.1. Figure C.8. Annex C of Eurocode 1, snow actions*

Because this building is placed in Svedmyra, the zone number is 2 and the characteristic snow load is 2.00 kN/m².
Based on this map, the following equation is used (Annex C, table C.1 Altitude – Snow load relationships):

\[ s_k = 0.790 \cdot Z + 0.375 \cdot \frac{A}{336} \]  \hspace{1cm} (A1.2)

where

A is the site altitude above Sea Level (m)

Z is the zone number given on the map

And with it the characteristic snow load is:

\[ s_k = 0.790 \cdot 2 + 0.375 \cdot \frac{41}{336} = 2.08 \text{ kN/m}^2 \]  \hspace{1cm} (A1.3)

Both numbers are correct for being used in the calculations but one has to be chosen and, in this case, 2.08 kN/m² is the one used because is the maximum between them.

For obtain \( \mu \), is necessary to know the type of the roof and in this case it is a duopitched roof.

The next picture show different cases for duopitched roofs:

![Figure A1.2. Figure 5.3 of Eurocode 1, snow actions. Snow load shape coefficients – duopitched roofs](image)

where

case (i) is for undrifting roofs

case (ii) and (iii) is for drifted roofs
In this building the case (ii) and (iii) are the same, therefore, only has to be calculated two cases. Then, it is necessary to obtain $\mu_1$ that is extracted from the following table:

<table>
<thead>
<tr>
<th>Angle of pitch of roof $\alpha$</th>
<th>$0^\circ \leq \alpha \leq 30^\circ$</th>
<th>$30^\circ &lt; \alpha &lt; 60^\circ$</th>
<th>$\alpha \geq 60^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_1$</td>
<td>0,8</td>
<td>0,8($60^\circ$ - $\alpha$)/$30$</td>
<td>0,0</td>
</tr>
<tr>
<td>$\mu_2$</td>
<td>0,8+$0,8$($\alpha$/30)</td>
<td>1,6</td>
<td>-</td>
</tr>
</tbody>
</table>

Hence, value for $\mu_1 = \mu_1 = 0,8$ in both cases, due to the angle of the pitch is less than $30^\circ$.

The thermal coefficient $C_t$ is used to reduce the value of the snow load if the roof of the building has high thermal conductivity but in this case is going to be supposed that it is a roof with a normal thermal conductivity and, therefore, $C_t = 1$.

Finally, it is necessary to obtain $C_e$ which depends on the topography of the building’s location. In this case the building is placed in a urbanization with buildings that have the same length and highness than it and due to this is going to be considerate a normal topography. Using the following table there is obtained that:

<table>
<thead>
<tr>
<th>Topography</th>
<th>$C_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windswept$^a$</td>
<td>0,8</td>
</tr>
<tr>
<td>Normal$^b$</td>
<td>1,0</td>
</tr>
<tr>
<td>Sheltered$^c$</td>
<td>1,2</td>
</tr>
</tbody>
</table>

$^a$ Windswept: flat unobstructed areas exposed on all sides without, or shelter afforded by terrain, higher construction works or trees.

$^b$ Normal: areas where there is no significant removal of snow by wind on construction work, because of terrain, other construction works or trees.

$^c$ Sheltered: areas in which the construction work being considered is considerably lower than the surrounding terrain or surrounded by high trees and/or surrounded by higher construction works.

Then, $C_e = 1$.

At last the snow load will be for case (i):
\[ s = \mu_1 \cdot C_o \cdot C_t \cdot s_k = 0.8 \cdot 1 \cdot 1 \cdot 2.08 = 1.66 \text{ kN/m}^2 \]  
(A1.4)

And for case (ii):

\[ s = \mu_1 \cdot C_o \cdot C_t \cdot s_k = 0.8 \cdot 1 \cdot 1 \cdot 2.08 = 1.66 \text{ kN/m}^2 \]  
(A1.5)

\[ s = \mu_1 \cdot C_o \cdot C_t \cdot s_k = 0.5 \cdot 0.8 \cdot 1 \cdot 1 \cdot 2.08 = 0.83 \text{ kN/m}^2 \]  
(A1.6)

A1.2 Wind

All of following calculations have been realized according to Eurocode 1 (EN 1991-1-4).

The procedure to obtain the wind actions passes for calculating the following values:

*Table A1.3. Table 5.1 of Eurocode 1, wind actions. Calculation procedures for determination of wind actions*

<table>
<thead>
<tr>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak velocity pressure ( q_p )</td>
</tr>
<tr>
<td>Basic wind velocity ( v_b )</td>
</tr>
<tr>
<td>Reference height ( z_o )</td>
</tr>
<tr>
<td>Terrain category</td>
</tr>
<tr>
<td>Characteristic peak velocity pressure ( q_p )</td>
</tr>
<tr>
<td>Turbulence Intensity ( I_v )</td>
</tr>
<tr>
<td>Mean wind velocity ( v_m )</td>
</tr>
<tr>
<td>Orography coefficient ( C_d(z) )</td>
</tr>
<tr>
<td>Roughness coefficient ( C_r(z) )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wind pressures, e.g. for cladding, fixings and structural parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal pressure coefficients ( C_p )</td>
</tr>
<tr>
<td>External pressure coefficient ( C_{pe} )</td>
</tr>
<tr>
<td>External wind pressure: ( w_e = q_p C_{pe} )</td>
</tr>
<tr>
<td>Internal wind pressure: ( w_i = q_p C_{pi} )</td>
</tr>
</tbody>
</table>
• **Terrain category**

For the election of terrain category is going to be chosen the one that correspond to Svedmyra.

*Table A1.4. Table 4.1, Eurocode 1, wind actions. Terrain categories and terrain parameters*

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

According to the table, the terrain category is III, therefore $z_0 = 0,3$ m and $z_{\text{min}} = 5$ m.

• **Basic wind velocity $v_b$**

$$v_b = c_{\text{dir}} \cdot c_{\text{season}} \cdot v_{b,0}$$  \hspace{1cm} (A1.7)

where

- $v_b$ is the basic wind velocity, defined as a function of wind direction and time of year at 10 m above ground terrain category II
- $v_{b,0}$ is the fundamental value of the basic wind velocity
- $c_{\text{dir}}$ is the directional factor
- $c_{\text{season}}$ is the season factor
For $v_{b,0}$ the value selected is 26 m/s according to the national annex for Sweden, and $C_{dir}$ and $C_{season}$ are factors reducing the effect of the wind, but the recommended values are 1 and, like it is necessary to obtain the worst case, these are going to be the ones used.

Finally:

$$ v_b = v_{b,0} \cdot C_{dir} \cdot C_{season} = 24 \cdot 1 \cdot 1 = 24 \text{ m/s} $$

- **Reference height $z_e$**

The reference height for duopitch roofs is the maximum height which in this case is $z_e = 14,55 \text{ m}$.

- **Characteristic peak velocity pressure $q_{b}$**

For calculate the characteristic peak velocity pressure it is used the following equation:

$$ q_b = \frac{1}{2} \cdot \rho \cdot v_b^2 = 0,5 \cdot 1,25 \cdot 24^2 = 360 \text{ N/m}^2 $$

(A1.8)

Where $\rho$ is the air density that in this case equal $1,25 \text{ kg/m}^3$.

- **Orography coefficient $c_o(z)$**

This value will be 1, recommended by Eurocode, unless otherwise specified in 4.3.3 of Eurocode 1, wind actions.

- **Turbulence intensity $I_v$**

$$ I_v(z) = \frac{\sigma_v}{\nu_m(z)} = \frac{k_l}{c_0(z) \ln (z/z_o)} \quad \text{for} \quad z_{min} \leq z \leq z_{max} $$

(A1.9)

$$ I_v(z) = I_v(z_{min}) \quad \text{for} \quad z < z_{min} $$

(A1.10)

In this case $z_{min} = 5 \text{ m}$, according to the table 4.1, wind actions, and $z = 12,55 \text{ m}$, due to this height the equation that has to be used is the first one, where $k_l = 1$, recommended by the Eurocode, $z = 12,55 \text{ m}$, $z_o = 0,3 \text{ m}$ and $c_o(z) = 1$
\[
I(z) = \frac{1}{1 \cdot \ln \left( \frac{12.55}{0.3} \right)} = 0.26
\]

- **Roughness coefficient \( c_r(z) \)**

For calculate this value it is necessary to use one of the following equations:

\[
c_r(z) = k_r \cdot \ln \left( \frac{z}{z_0} \right) \quad \text{for } z_{\text{min}} \leq z \leq z_{\text{max}} \quad (A1.11)
\]

\[
c_r(z) = c_r(z_{\text{min}}) \quad \text{for } z \leq z_{\text{min}} \quad (A1.12)
\]

where

- \( z_0 \) is the roughness length
- \( k_r \) terrain factor depending on the roughness length \( z_0 \) calculated using

\[
k_r = 0.19 \cdot \left( \frac{z_0}{z_{0,\text{II}}} \right)^{0.07} \quad (A1.13)
\]

where

- \( z_{0,\text{II}} = 0.05 \) m (terrain category II, table 4.1 of Eurocode)
- \( z_{\text{min}} \) is the minimum height defined in table 4.1 of Eurocode
- \( z_{\text{max}} \) is to be taken as 200 m, unless otherwise specified in the National Annex of Sweden

In this case:

\[
k_r = 0.19 \cdot \left( \frac{0.3}{0.05} \right)^{0.07} = 0.22
\]

\[
c_r(z) = 0.22 \cdot \ln \left( \frac{12.55}{0.3} \right) = 0.84
\]

- **Mean wind velocity \( v_m \)**

\( v_m \) is calculated using the following equation:
\[ v_m = c_r(z) \cdot c_0(z) \cdot v_b \]  
(A1.14)

And utilizing the values obtained at the previous paragraphs:

\[ v_m = 0,84 \cdot 1 \cdot 24 = 20,07 \text{ m/s} \]

With all these values it is obtained the following coefficient (Eq. A1.15):

\[ c_e = \frac{q_p(z)}{q_b} = \left[ 1 + 7 \cdot l_v(z) \right] \cdot \frac{1}{2} \cdot \rho \cdot v_m^2(z) = \left[ 1 + 7 \cdot 0,26 \right] \cdot 0,5 \cdot 1,25 \cdot 20,07^2 = 1,96 \]

- Internal and external wind pressure:

There are calculated with the following equations:

\[ w_e = c_e \cdot c_i \cdot q_p \]  
(A1.16)
\[ w_i = 0,8 \cdot w_e \]  
(A1.17)

For obtain these results is necessary a table for a duopitch roofs and for façades:

**ROOF**

<table>
<thead>
<tr>
<th>Pitch Angle 15°</th>
<th>Zone for wind direction θ=0°</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C_{pe,10}</td>
<td>C_{pe,1}</td>
<td>C_{pe,10}</td>
<td>C_{pe,1}</td>
<td>C_{pe,10}</td>
</tr>
<tr>
<td>-0,9</td>
<td>-2,0</td>
<td>-0,8</td>
<td>-1,5</td>
<td>-0,3</td>
<td>-0,4</td>
<td>-1,0</td>
</tr>
<tr>
<td>+0,2</td>
<td>+0,2</td>
<td>+0,2</td>
<td>+0,2</td>
<td>+0,0</td>
<td>+0,0</td>
<td></td>
</tr>
</tbody>
</table>

\(^3\) Due to the table ranges between 15° and 30° but the pitch angle is 20° is going to take the coefficients of the most unflattering, in this case 15°

\(^4\) C_{pe,10} is chosen because the surfaces of the roof and façades are larger than 10 m²

\(^5\) The values marked are the ones used for the calculations
Figure A1.3. Schema from Eurocode about wind load distribution on the roof ($\theta=0^\circ$)

\[ b = 46.4 \text{ m}; e = \min(46.4; 2 \cdot 12.55) = 25.1 \text{ m} \]
Figure A2.4. Division of the building (simple schema) ($\theta=0^\circ$)

Table A1.6. Coefficients for calculate wind load on the roof ($\theta=90^\circ$)

<table>
<thead>
<tr>
<th>Pitch Angle $15^\circ$</th>
<th>Zone for wind direction $\theta=90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>$C_{pe_{10}}$</td>
</tr>
<tr>
<td>-1,3</td>
<td>-2,0</td>
</tr>
<tr>
<td></td>
<td>-1,3</td>
</tr>
</tbody>
</table>
Figure A1.5. Schema from Eurocode about wind load distribution on the roof ($\theta = 90^\circ$)

\[ b = 10,1 \text{ m}; e = \min(10,1; 2 \cdot 14,55) = 10,1 \text{ m} \]

Figure A1.6. Division of the building (simple schema) ($\theta = 90^\circ$)
FAÇADE

Here, it can be seen 2 different cases:

![Diagram](image1)

*Figure A1.7. Schema from Eurocode about wind load distribution on the façade*

The first one is:

\[ b = 46.4 \text{ m}; e = \min(46.4; 2 \cdot 12.55) = 25.1 \text{ m}; e > d = 10.1 \text{ m}; \frac{h}{d} = 1.445 \]

![Diagram](image2)

*Figure A1.8. Schema from Eurocode about wind load distribution on the façade (e≥d)*
The second one is:

\[ b = 10,1 \text{ m}; e = \min(10,1; 2 \cdot 12,55) = 10,1 \text{ m}; e < d = 46,4 \text{ m}; \frac{h}{d} = 0,335 \]

![Elevation for e < d](image)

*Figure A1.9. Schema from Eurocode about wind load distribution on the façade (e<d)*

The building has 4 façades, but only two different cases of wind in theirs.

*Table A1.7. Coefficients for calculate wind load on the façade*

<table>
<thead>
<tr>
<th>Zone</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>h/d</td>
<td>C_{pe,10}</td>
<td>C_{pe,1}</td>
<td>C_{pe,10}</td>
<td>C_{pe,1}</td>
<td>C_{pe,10}</td>
</tr>
<tr>
<td>5</td>
<td>-1,2</td>
<td>-1,4</td>
<td>-0,8</td>
<td>-1,1</td>
<td>-0,5</td>
</tr>
<tr>
<td>1</td>
<td>-1,2</td>
<td>-1,4</td>
<td>-0,8</td>
<td>-1,1</td>
<td>-0,5</td>
</tr>
<tr>
<td>&lt;=0,25</td>
<td>-1,2</td>
<td>-1,4</td>
<td>-0,8</td>
<td>-1,1</td>
<td>-0,5</td>
</tr>
</tbody>
</table>

\(^{6}\) For each case is chosen the h/d immediately superior
Finally, the results are:

**Table A1.8. Pressure on the roof and on the façades of the building**

<table>
<thead>
<tr>
<th>ROOF</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta = 0^\circ$ (wind)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$w_i$ (kN/m$^2$)</td>
<td>-1.24</td>
<td>-1.11</td>
<td>-0.41</td>
<td>-0.55</td>
<td>-1.38</td>
</tr>
<tr>
<td>$w_e$ (kN/m$^2$)</td>
<td>-1.12</td>
<td>-1.00</td>
<td>-0.37</td>
<td>-0.50</td>
<td>-1.24</td>
</tr>
<tr>
<td>$\theta = 90^\circ$ (wind)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$w_i$ (kN/m$^2$)</td>
<td>-1.80</td>
<td>-1.80</td>
<td>-0.83</td>
<td>-0.69</td>
<td>-</td>
</tr>
<tr>
<td>$w_e$ (kN/m$^2$)</td>
<td>-1.62</td>
<td>-1.62</td>
<td>-0.75</td>
<td>-0.62</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FAÇADE</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>First case</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$w_i$ (kN/m$^2$)</td>
<td>-1.66</td>
<td>-1.11</td>
<td>-</td>
<td>1.11</td>
<td>-0.97</td>
</tr>
<tr>
<td>$w_e$ (kN/m$^2$)</td>
<td>-1.49</td>
<td>-1.00</td>
<td>-</td>
<td>1.00</td>
<td>-0.87</td>
</tr>
<tr>
<td>Second case</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$w_i$ (kN/m$^2$)</td>
<td>-1.66</td>
<td>-1.11</td>
<td>-0.69</td>
<td>1.11</td>
<td>-0.69</td>
</tr>
<tr>
<td>$w_e$ (kN/m$^2$)</td>
<td>-1.49</td>
<td>-1.00</td>
<td>-0.62</td>
<td>1.00</td>
<td>-0.62</td>
</tr>
</tbody>
</table>

The following images show the distribution of the wind load in the façades of the building.
Façade, first case

Figure A1.10. Pressure on the façades of the building (θ=0°)
A1.3 Dead Loads

In the following tables is going to show the part of each element used for make a volume and its respective self weight.

Wall between modules:

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum</td>
<td>0.1185</td>
</tr>
<tr>
<td>Gypsum/Fermacell</td>
<td>0.1185</td>
</tr>
<tr>
<td>Acquis</td>
<td>0.035625</td>
</tr>
<tr>
<td>Min. wool</td>
<td>0.02375</td>
</tr>
</tbody>
</table>

Total: **0.296 kN/m²**

Exterior wall:

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum</td>
<td>0.1027</td>
</tr>
<tr>
<td>Gypsum</td>
<td>0.1027</td>
</tr>
<tr>
<td>Acquis</td>
<td>0.06375</td>
</tr>
<tr>
<td>Min. wool</td>
<td>0.0425</td>
</tr>
<tr>
<td>GU</td>
<td>0.0711</td>
</tr>
<tr>
<td>Stenull</td>
<td>0.0125</td>
</tr>
<tr>
<td>Serporoc</td>
<td>0.136</td>
</tr>
</tbody>
</table>

Total: **0.531**
Floor:

Table A1.11 Dead load of the floor

<table>
<thead>
<tr>
<th>Material</th>
<th>Load (kN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parquet</td>
<td>0.098</td>
</tr>
<tr>
<td>Gipsum</td>
<td>0.1027</td>
</tr>
<tr>
<td>Particle board</td>
<td>0.154</td>
</tr>
<tr>
<td>Glulam</td>
<td>0.07875</td>
</tr>
<tr>
<td>Stenull</td>
<td>0.02375</td>
</tr>
<tr>
<td>Plywood</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Total 0.517 kN/m²

Ceiling:

Table A1.12 Dead load of the ceiling

<table>
<thead>
<tr>
<th>Material</th>
<th>Load (kN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. wool</td>
<td>0.03</td>
</tr>
<tr>
<td>Acquis</td>
<td>0.045</td>
</tr>
<tr>
<td>Gipsum</td>
<td>0.1027</td>
</tr>
<tr>
<td>Gipsum</td>
<td>0.1185</td>
</tr>
</tbody>
</table>

Total 0.296 kN/m²

Roof (inside):

Table A1.13 Dead load of the roof

<table>
<thead>
<tr>
<th>Material</th>
<th>Load (kN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lösull</td>
<td>0.105</td>
</tr>
<tr>
<td>Truss</td>
<td>0.039375</td>
</tr>
<tr>
<td>Plate</td>
<td>0.07</td>
</tr>
<tr>
<td>Lath</td>
<td>0.0315</td>
</tr>
<tr>
<td>Truss</td>
<td>0.039375</td>
</tr>
</tbody>
</table>

Total 0.285 kN/m²

Figure A1.14 Characteristics of floor used by Moelven

Figure A1.15 Characteristics of ceiling used by Moelven

Figure A1.16 Characteristics of roof (inside and outside) used by Moelven
Table A1.14 Dead loads of the volumetric

<table>
<thead>
<tr>
<th>Load</th>
<th>kN/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{SVY}$ (outside wall)</td>
<td>0.531</td>
</tr>
<tr>
<td>$g_{SLSV}$ (wall between modules)</td>
<td>0.296</td>
</tr>
<tr>
<td>$g_{SBL}$ (floor)</td>
<td>0.517</td>
</tr>
<tr>
<td>$g_{SN}$ (ceiling)</td>
<td>0.296</td>
</tr>
<tr>
<td>$g_{ATY}$ (roof)</td>
<td>0.285</td>
</tr>
</tbody>
</table>

For the trä8 system the self weight of the beams and the columns are only the density of them multiplied per the volume of each. A little bit more complicate is the calculation of the floor due to is a composite between to kind of Kerto-Q and Kerto-S. The cassette used for the floors is made with 4 pieces with the following shape:

![Figure A1.17. Cassette of trä8 system](image)

Knowing the dimensions of each piece, taken from a standard piece of deck, and the density of them, the self weight of the floor was calculated:

Table A1.15 Mesures of a cassette

<table>
<thead>
<tr>
<th>Mesures (mm)</th>
<th>width</th>
<th>depth</th>
<th>length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big deck</td>
<td>1800</td>
<td>27</td>
<td>8000</td>
</tr>
<tr>
<td>Small deck</td>
<td>900</td>
<td>27</td>
<td>8000</td>
</tr>
<tr>
<td>T (2 of them)</td>
<td>39</td>
<td>360</td>
<td>8000</td>
</tr>
<tr>
<td>L (4 of them)</td>
<td>39</td>
<td>360</td>
<td>8000</td>
</tr>
<tr>
<td></td>
<td>170</td>
<td>39</td>
<td>8000</td>
</tr>
</tbody>
</table>
Table A1.16 Volume of every element of a cassette

<table>
<thead>
<tr>
<th>Cassette</th>
<th>Kerto Q</th>
<th>Kerto S</th>
</tr>
</thead>
<tbody>
<tr>
<td>big panel volume (m³)</td>
<td>0,39</td>
<td></td>
</tr>
<tr>
<td>little panel volume (m³)</td>
<td>0,19</td>
<td></td>
</tr>
<tr>
<td>T (m³)</td>
<td></td>
<td>0,21</td>
</tr>
<tr>
<td>L(m³)</td>
<td></td>
<td>0,17</td>
</tr>
</tbody>
</table>

Table A1.17 Calculation of the pressure made by the cassette.

<table>
<thead>
<tr>
<th></th>
<th>Big panel</th>
<th>Small panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (m³)</td>
<td>1,13</td>
<td>0,53</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>576,99</td>
<td>267,81</td>
</tr>
<tr>
<td>Load (kN)</td>
<td>5,66</td>
<td>2,63</td>
</tr>
<tr>
<td>Total (kN)</td>
<td>25,27</td>
<td></td>
</tr>
<tr>
<td>Pressure (kN/m²)</td>
<td>0,39</td>
<td></td>
</tr>
</tbody>
</table>

Finally, the last dead load that has to be calculated is the one for the furniture but this one can be taken from the Eurocode and its value for offices and dwellings is 0,5 kN/m².
APPENDIX 2. RESULTS OF THE PREMODELS

Here are showed the results obtained with FEM-Design. It is presented two types of results: the lineal distribution and the maximum of the original distribution in each wall.

VERTICAL LOADS

Knowing the following loads for the volumetric system:

*Table A.2.1. Loads applied for the calculation of the vertical loads*

<table>
<thead>
<tr>
<th>Load</th>
<th>kN/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g_{AYV} ) (outside wall)</td>
<td>0,531</td>
</tr>
<tr>
<td>( g_{LSV} ) (wall between modules)</td>
<td>0,296</td>
</tr>
<tr>
<td>( g_{SRL} ) (floor)</td>
<td>0,517</td>
</tr>
<tr>
<td>( g_{SN} ) (ceiling)</td>
<td>0,296</td>
</tr>
<tr>
<td>( g_{AYT} ) (roof)</td>
<td>0,285</td>
</tr>
<tr>
<td>( s_d ) (snow)</td>
<td>1,66</td>
</tr>
<tr>
<td>( n_d ) (furniture)</td>
<td>0,5</td>
</tr>
</tbody>
</table>

The calculation of the vertical loads has given the next values:

Hand Calculations

First at all is going to be explained how to calculate the areas which the module is divided and once they are calculated the load is obtained by multiply this area per its appropriated load.
Effective areas (for one wall)

- **Roofs (Horizontal)**
  - Load area snow = Load area roof = Half of the whole area of the roof
  - Load area useful = Half of the area of the volume without walls (300 mm each wall)

- **Walls (Vertical)**
  - Load area rest (walls area) = Half of the area of the walls (not outside or between volumes)
  - Load area between corridors = Surface of the wall in vertical
  - Load area outside wall = Surface of the wall in a vertical way

Loads (for one wall)

**External wall**

1. **Snow** = snow area \cdot snow load
2. **Roof self weight** = snow area \cdot roof self weight
3. **Ext. Walls self weight** = ext. walls area \cdot ext. walls self weight \cdot n° floors
4. **Whole ceiling self weight** = n° load floors \cdot walls area \cdot (furniture weight \cdot joists weight \cdot ceiling weight)

Everything added and divided per width (longitude of external walls)

**Wall between modules**

1. **Whole ceiling weight** = n° load floors \cdot useful area \cdot (furniture weight \cdot joists load \cdot ceiling weight)
2. **Walls between volumes self weight** = n° floors \cdot walls between volumes areas \cdot walls between volumes self weight

Everything added and divided per length (longitude of between modules walls)

When the formulas for every area and load are clear the next step is calculate for each pre-model the loads.
For one module

Table A.2.2 Values for one module. Hand calculation.

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length volume</td>
<td>8,384 m</td>
</tr>
<tr>
<td>Width volume</td>
<td>3,321 m</td>
</tr>
<tr>
<td>Load area snow</td>
<td>13.92 m²</td>
</tr>
<tr>
<td>Load area useful</td>
<td>13.01 m²</td>
</tr>
<tr>
<td>Load area rest</td>
<td>0.91 m²</td>
</tr>
<tr>
<td>Load area YV (surface outside wall)</td>
<td>8.34 m²</td>
</tr>
<tr>
<td>Load area LS (surface wall between volumes)</td>
<td>21.04 m²</td>
</tr>
<tr>
<td>Number of floors</td>
<td>4</td>
</tr>
<tr>
<td>Number of load floors</td>
<td>3</td>
</tr>
<tr>
<td>External wall</td>
<td>12.40 kN/m</td>
</tr>
<tr>
<td>Wall between volume</td>
<td>10.86 kN/m</td>
</tr>
</tbody>
</table>

LINEAL LOADS

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>selfweight</td>
<td></td>
</tr>
<tr>
<td>outerwall</td>
<td>4.00 kN/m</td>
</tr>
<tr>
<td>wall between</td>
<td>2.23 kN/m</td>
</tr>
<tr>
<td>ceiling+floor+furniture (out wall)</td>
<td>1.44 kN/m</td>
</tr>
<tr>
<td>ceiling+floor+furniture (wall bet)</td>
<td>8.15 kN/m</td>
</tr>
<tr>
<td>snow (out wall)</td>
<td>6.96 kN/m</td>
</tr>
<tr>
<td>roof (wall bet)</td>
<td>0.47 kN/m</td>
</tr>
</tbody>
</table>
For two modules

Table A.2.3 Values for two modules. Hand calculation.

<table>
<thead>
<tr>
<th></th>
<th>Module 1</th>
<th>Module 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length volume:</td>
<td>8,384 m</td>
<td>8,384 m</td>
</tr>
<tr>
<td>Width volume:</td>
<td>3,321 m</td>
<td>3,946 m</td>
</tr>
<tr>
<td>Load area snow:</td>
<td>13,92 m²</td>
<td>16,54 m²</td>
</tr>
<tr>
<td>Load area useful:</td>
<td>13,26 m²</td>
<td>15,76 m²</td>
</tr>
<tr>
<td>Load area rest:</td>
<td>0,66 m²</td>
<td>0,78 m²</td>
</tr>
<tr>
<td>Load area YV (surface outside wall):</td>
<td>8,34 m²</td>
<td>9,90 m²</td>
</tr>
<tr>
<td>Load area LS (surface wall between volumes):</td>
<td>21,04 m²</td>
<td>21,04 m²</td>
</tr>
<tr>
<td>number of floors</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>number of load floors</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>external wall</td>
<td>12,00 kN/m</td>
<td>12,00 kN/m</td>
</tr>
<tr>
<td>wall between volume</td>
<td>11,02 kN/m</td>
<td>12,67 kN/m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Lineal Loads</th>
<th>Middle wall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Outer wall</td>
<td>4.00 kN/m</td>
</tr>
<tr>
<td></td>
<td>Wall between</td>
<td>2.23 kN/m</td>
</tr>
<tr>
<td>ceiling+floor+furniture (out wall)</td>
<td>1.04 kN/m</td>
<td>1.04 kN/m</td>
</tr>
<tr>
<td>ceiling+floor+furniture (wall between modules)</td>
<td>8.31 kN/m</td>
<td>9.88 kN/m</td>
</tr>
<tr>
<td>snow (out wall)</td>
<td>6.96 kN/m</td>
<td>6.96 kN/m</td>
</tr>
<tr>
<td>roof (wall between modules)</td>
<td>0.47 kN/m</td>
<td>0.56 kN/m</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>21.45 kN/m</td>
<td></td>
</tr>
</tbody>
</table>
For four modules:

<table>
<thead>
<tr>
<th>Module 1</th>
<th>Module 2</th>
<th>Module 3</th>
<th>Module 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length volume:</td>
<td>8,384 m</td>
<td>8,384 m</td>
<td>5,649 m</td>
</tr>
<tr>
<td>Width volume:</td>
<td>3,321 m</td>
<td>3,946 m</td>
<td>4,021 m</td>
</tr>
<tr>
<td>Load area snow:</td>
<td>13,92 m²</td>
<td>16,54 m²</td>
<td>11,36 m²</td>
</tr>
<tr>
<td>Load area useful:</td>
<td>13,26 m²</td>
<td>15,76 m²</td>
<td>10,56 m²</td>
</tr>
<tr>
<td>Load area rest:</td>
<td>0,66 m²</td>
<td>0,78 m²</td>
<td>0,80 m²</td>
</tr>
<tr>
<td>Load area YV (surface outside wall):</td>
<td>8,34 m²</td>
<td>9,90 m²</td>
<td>10,09 m²</td>
</tr>
<tr>
<td>Load area LS (surface wall between volumes):</td>
<td>21,04 m²</td>
<td>21,04 m²</td>
<td>14,18 m²</td>
</tr>
<tr>
<td>number of floors</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>number of load floors</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>external wall</td>
<td>12,00 kN/m</td>
<td>12,00 kN/m</td>
<td>9,73 kN/m</td>
</tr>
<tr>
<td>wall between volume</td>
<td>11,02 kN/m</td>
<td>12,67 kN/m</td>
<td>12,63 kN/m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>selfweight</th>
<th>LINEAL LOADS</th>
<th>Middle wall 1</th>
<th>Middle wall 2</th>
<th>Middle transversal</th>
</tr>
</thead>
<tbody>
<tr>
<td>outerwall</td>
<td>4,00 kN/m</td>
<td>4,00 kN/m</td>
<td>4,00 kN/m</td>
<td>4,00 kN/m</td>
</tr>
<tr>
<td>wall between</td>
<td>2,23 kN/m</td>
<td>2,23 kN/m</td>
<td>2,23 kN/m</td>
<td>2,23 kN/m</td>
</tr>
<tr>
<td>ceiling+floor+furniture</td>
<td>1,04 kN/m</td>
<td>1,04 kN/m</td>
<td>1,04 kN/m</td>
<td>1,04 kN/m</td>
</tr>
<tr>
<td>(out wall)</td>
<td>8,31 kN/m</td>
<td>9,88 kN/m</td>
<td>9,82 kN/m</td>
<td>18,19 kN/m</td>
</tr>
<tr>
<td>ceiling+floor+furniture</td>
<td>6,96 kN/m</td>
<td>6,96 kN/m</td>
<td>4,69 kN/m</td>
<td>3,71 kN/m</td>
</tr>
<tr>
<td>(wall bet)</td>
<td>0,47 kN/m</td>
<td>0,56 kN/m</td>
<td>0,57 kN/m</td>
<td>1,04 kN/m</td>
</tr>
<tr>
<td>snow (out wall)</td>
<td>8,40 kN/m</td>
<td>8,40 kN/m</td>
<td>8,40 kN/m</td>
<td>8,40 kN/m</td>
</tr>
<tr>
<td>roof (wall bet)</td>
<td>8,40 kN/m</td>
<td>8,40 kN/m</td>
<td>8,40 kN/m</td>
<td>8,40 kN/m</td>
</tr>
<tr>
<td>TOTAL</td>
<td>21,45 kN/m</td>
<td>23,06 kN/m</td>
<td>22,87 kN/m</td>
<td>14,48 kN/m</td>
</tr>
</tbody>
</table>

81
For half of the first storey of volumetric system:

**Table A.2.4 Values for half of the first storey of volume system. Hand calculation.**

<table>
<thead>
<tr>
<th></th>
<th>Module 1</th>
<th>Module 2</th>
<th>Module 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length volume</td>
<td>8,384 m</td>
<td>8,384 m</td>
<td>10,118 m</td>
</tr>
<tr>
<td>Width volume</td>
<td>3,321 m²</td>
<td>3,946 m²</td>
<td>4,021 m²</td>
</tr>
<tr>
<td>Load area snow</td>
<td>13,92 m²</td>
<td>16,54 m²</td>
<td>20,34 m²</td>
</tr>
<tr>
<td>Load area useful</td>
<td>13,49 m²</td>
<td>15,59 m²</td>
<td>19,37 m²</td>
</tr>
<tr>
<td>Load area rest</td>
<td>0,91 m²</td>
<td>0,95 m²</td>
<td>0,97 m²</td>
</tr>
<tr>
<td>Load area YV (surface outside wall)</td>
<td>8,34 m²</td>
<td>9,90 m²</td>
<td>10,09 m²</td>
</tr>
<tr>
<td>Load area LS (surface wall between volumes)</td>
<td>21,04 m²</td>
<td>21,04 m²</td>
<td>25,40 m²</td>
</tr>
<tr>
<td>number of floors</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>number of load floors</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>external wall</td>
<td>12,40 kN/m</td>
<td>12,23 kN/m</td>
<td>13,67 kN/m</td>
</tr>
<tr>
<td>wall between volume</td>
<td>11,16 kN/m</td>
<td>12,56 kN/m</td>
<td>12,86 kN/m</td>
</tr>
</tbody>
</table>

**LINEAL LOADS**

<table>
<thead>
<tr>
<th>selfweight</th>
<th>LINEAL LOADS</th>
<th>Middle wall 1</th>
<th>Middle wall 2</th>
<th>Middle wall 3</th>
<th>Middle wall 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>outerwall</td>
<td>4.00 kN/m</td>
<td>4.00 kN/m</td>
<td>4.00 kN/m</td>
<td>2.23 kN/m</td>
<td>2.23 kN/m</td>
</tr>
<tr>
<td>wall between</td>
<td>2.23 kN/m</td>
<td>2.23 kN/m</td>
<td>2.23 kN/m</td>
<td>2.23 kN/m</td>
<td>2.23 kN/m</td>
</tr>
<tr>
<td>ceiling+floor+furniture (out wall)</td>
<td>1.44 kN/m</td>
<td>1.27 kN/m</td>
<td>1.27 kN/m</td>
<td>1.27 kN/m</td>
<td>1.27 kN/m</td>
</tr>
<tr>
<td>ceiling+floor+furniture (wall bet)</td>
<td>8.45 kN/m</td>
<td>9.77 kN/m</td>
<td>10.06 kN/m</td>
<td>18.22 kN/m</td>
<td>19.82 kN/m</td>
</tr>
<tr>
<td>snow (out wall)</td>
<td>6.96 kN/m</td>
<td>6.96 kN/m</td>
<td>8.40 kN/m</td>
<td>1.04 kN/m</td>
<td>1.14 kN/m</td>
</tr>
<tr>
<td>roof (wall bet)</td>
<td>0.47 kN/m</td>
<td>0.56 kN/m</td>
<td>0.57 kN/m</td>
<td>1.15 kN/m</td>
<td>1.15 kN/m</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>21.49 kN/m</td>
<td>23.19 kN/m</td>
<td>23.49 kN/m</td>
<td>22.89 kN/m</td>
<td></td>
</tr>
</tbody>
</table>
Complete volumetric system, e.g. 3 storeys:

For each module the walls are distributed as follow

<table>
<thead>
<tr>
<th>Module</th>
<th>Wall 1</th>
<th>Wall 2</th>
<th>Wall 3</th>
<th>Wall 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12,40</td>
<td>11,16</td>
<td>12,40</td>
<td>21,10</td>
</tr>
<tr>
<td>2</td>
<td>12,40</td>
<td>21,10</td>
<td>12,40</td>
<td>22,59</td>
</tr>
<tr>
<td>3</td>
<td>13,84</td>
<td>12,79</td>
<td>23,04</td>
<td>13,84</td>
</tr>
<tr>
<td>4</td>
<td>13,84</td>
<td>23,36</td>
<td>13,84</td>
<td>12,79</td>
</tr>
<tr>
<td>5</td>
<td>12,40</td>
<td>22,59</td>
<td>12,40</td>
<td>21,10</td>
</tr>
<tr>
<td>6</td>
<td>12,40</td>
<td>21,10</td>
<td>12,40</td>
<td>22,73</td>
</tr>
<tr>
<td>7</td>
<td>12,40</td>
<td>22,73</td>
<td>12,40</td>
<td>22,73</td>
</tr>
<tr>
<td>8</td>
<td>12,40</td>
<td>22,73</td>
<td>12,40</td>
<td>22,59</td>
</tr>
<tr>
<td>9</td>
<td>13,84</td>
<td>12,79</td>
<td>23,04</td>
<td>13,84</td>
</tr>
<tr>
<td>10</td>
<td>13,84</td>
<td>23,36</td>
<td>13,84</td>
<td>12,79</td>
</tr>
<tr>
<td>11</td>
<td>12,40</td>
<td>22,59</td>
<td>12,40</td>
<td>21,10</td>
</tr>
<tr>
<td>12</td>
<td>12,40</td>
<td>21,10</td>
<td>12,40</td>
<td>11,16</td>
</tr>
</tbody>
</table>

**Fem-Design**

**Table A.2.6 Results of FEM-Design for 1 module**

<table>
<thead>
<tr>
<th>Wall</th>
<th>Lineal distribution (kN/m)</th>
<th>Original distribution (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long exterior walls</td>
<td>11,18</td>
<td>12,73</td>
</tr>
<tr>
<td>Short exterior walls</td>
<td>11,71</td>
<td>13,08</td>
</tr>
</tbody>
</table>

7 This wall has two values because one of them corresponds to the wall that excels the building
### Table A.2.7 Results of FEM-Design for 2 modules

<table>
<thead>
<tr>
<th>Module</th>
<th>Wall</th>
<th>Lineal distribution (kN/m)</th>
<th>Original distribution (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Long exterior wall</td>
<td>11,91</td>
<td>13,37</td>
</tr>
<tr>
<td>1-2</td>
<td>Wall between modules</td>
<td>20,47</td>
<td>22,53</td>
</tr>
<tr>
<td>2</td>
<td>Long exterior wall</td>
<td>13,38</td>
<td>14,81</td>
</tr>
<tr>
<td>1-2</td>
<td>Short exterior walls</td>
<td>13,52</td>
<td>16,19</td>
</tr>
</tbody>
</table>

### Table A.2.8 Results of FEM-Design for 4 modules

<table>
<thead>
<tr>
<th>Module</th>
<th>Wall</th>
<th>Lineal distribution (kN/m)</th>
<th>Original distribution (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Long exterior wall</td>
<td>11,33</td>
<td>14,01</td>
</tr>
<tr>
<td>1-2</td>
<td>Wall between modules</td>
<td>19,08</td>
<td>20,80</td>
</tr>
<tr>
<td>1 and 2</td>
<td>Short exterior wall (Top)</td>
<td>14,89</td>
<td>10,30</td>
</tr>
<tr>
<td>1 and 2</td>
<td>Short exterior wall (Bottom)</td>
<td>13,88</td>
<td>18,13</td>
</tr>
<tr>
<td>2-3</td>
<td>Wall between modules</td>
<td>19,77</td>
<td>23,07</td>
</tr>
<tr>
<td>2-4</td>
<td>Wall between modules</td>
<td>19,64</td>
<td>23,07</td>
</tr>
<tr>
<td>3</td>
<td>Short exterior wall, module 2 side</td>
<td>14,75</td>
<td>17,48</td>
</tr>
<tr>
<td>3-4</td>
<td>Transversal wall</td>
<td>16,40</td>
<td>21,55</td>
</tr>
<tr>
<td>3</td>
<td>Short exterior wall</td>
<td>11,59</td>
<td>9,43</td>
</tr>
<tr>
<td>3</td>
<td>Long exterior wall</td>
<td>12,74</td>
<td>15,45</td>
</tr>
<tr>
<td>4</td>
<td>Short exterior wall</td>
<td>13,88</td>
<td>18,13</td>
</tr>
<tr>
<td>4</td>
<td>Long exterior wall</td>
<td>12,74</td>
<td>15,45</td>
</tr>
</tbody>
</table>
### Table A.2.9 Results of FEM-Design for half of the first storey of volumetric system

<table>
<thead>
<tr>
<th>Module</th>
<th>Wall</th>
<th>Lineal distribution (kN/m)</th>
<th>Original distribution (kN/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Long exterior wall</td>
<td>11.29</td>
<td>12.43</td>
</tr>
<tr>
<td>1-2</td>
<td>Wall between modules</td>
<td>18.78</td>
<td>21.02</td>
</tr>
<tr>
<td>1 and 2</td>
<td>Short exterior wall (Top)</td>
<td>14.67</td>
<td>17.00</td>
</tr>
<tr>
<td>1 and 2</td>
<td>Short exterior wall (Bottom)</td>
<td>15.07</td>
<td>18.33</td>
</tr>
<tr>
<td>2-3</td>
<td>Wall between modules</td>
<td>20.87</td>
<td>22.74</td>
</tr>
<tr>
<td>3</td>
<td>Short exterior wall, module 2 side</td>
<td>14.79</td>
<td>15.38</td>
</tr>
<tr>
<td>3 and 4</td>
<td>Short exterior wall (Top)</td>
<td>14.95</td>
<td>17.93</td>
</tr>
<tr>
<td>3 and 4</td>
<td>Short exterior wall (Bottom)</td>
<td>15.07</td>
<td>18.33</td>
</tr>
<tr>
<td>3-4</td>
<td>Wall between modules</td>
<td>21.52</td>
<td>23.27</td>
</tr>
<tr>
<td>4-5</td>
<td>Wall between modules</td>
<td>20.83</td>
<td>22.73</td>
</tr>
<tr>
<td>4</td>
<td>Short exterior wall, module 5 side</td>
<td>15.29</td>
<td>17.28</td>
</tr>
<tr>
<td>5 and 6</td>
<td>Short exterior wall (Top)</td>
<td>14.70</td>
<td>17.28</td>
</tr>
<tr>
<td>5 and 6</td>
<td>Short exterior wall (Bottom)</td>
<td>15.07</td>
<td>18.33</td>
</tr>
<tr>
<td>5-6</td>
<td>Wall between modules</td>
<td>19.80</td>
<td>22.34</td>
</tr>
<tr>
<td>6</td>
<td>Long exterior wall</td>
<td>12.94</td>
<td>14.42</td>
</tr>
</tbody>
</table>

Knowing that each module is divided as follows:
The values of the reactions in every module are the following ones:

Table A.2.10 Results of FEM-Design for the whole structure of volumetric system

<table>
<thead>
<tr>
<th>Module</th>
<th>Wall 1</th>
<th>Wall 2</th>
<th>Wall 3</th>
<th>Wall 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.44</td>
<td>12.72</td>
<td>15.69</td>
<td>17.75</td>
</tr>
<tr>
<td>2</td>
<td>14.44</td>
<td>17.75</td>
<td>15.69</td>
<td>19.94</td>
</tr>
<tr>
<td>3</td>
<td>15.32</td>
<td>16.72</td>
<td>19.94&lt;sup&gt;8&lt;/sup&gt;</td>
<td>15.69</td>
</tr>
<tr>
<td>4</td>
<td>15.32</td>
<td>20.65</td>
<td>15.69</td>
<td>17.2</td>
</tr>
<tr>
<td>5</td>
<td>15.97</td>
<td>20.09</td>
<td>15.69</td>
<td>19.25</td>
</tr>
<tr>
<td>6</td>
<td>15.97</td>
<td>19.25</td>
<td>15.69</td>
<td>19.62</td>
</tr>
<tr>
<td>7</td>
<td>15.97</td>
<td>19.62</td>
<td>15.69</td>
<td>19.36</td>
</tr>
<tr>
<td>8</td>
<td>15.97</td>
<td>19.36</td>
<td>15.69</td>
<td>19.95</td>
</tr>
<tr>
<td>9</td>
<td>15.29</td>
<td>17.07</td>
<td>19.95&lt;sup&gt;8&lt;/sup&gt;</td>
<td>15.69</td>
</tr>
<tr>
<td>10</td>
<td>15.29</td>
<td>20.58</td>
<td>15.69</td>
<td>17.01</td>
</tr>
<tr>
<td>11</td>
<td>14.54</td>
<td>19.72</td>
<td>15.69</td>
<td>17.77</td>
</tr>
<tr>
<td>12</td>
<td>14.54</td>
<td>17.77</td>
<td>15.69</td>
<td>12.65</td>
</tr>
</tbody>
</table>

<sup>8</sup> This wall has two values because one of them corresponds to the wall that excels the building.
Table A.2.11 Results of FEM-Design for the whole structure of volumetric system

<table>
<thead>
<tr>
<th>Module</th>
<th>Wall 1</th>
<th>Wall 2</th>
<th>Wall 3</th>
<th>Wall 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13,48</td>
<td>12,53</td>
<td>13,46</td>
<td>19,07</td>
</tr>
<tr>
<td>2</td>
<td>14,9</td>
<td>19,07</td>
<td>15</td>
<td>20,87</td>
</tr>
<tr>
<td>3</td>
<td>15,14</td>
<td>17,08</td>
<td>20,87&lt;sup&gt;9&lt;/sup&gt;</td>
<td>15,87</td>
</tr>
<tr>
<td>4</td>
<td>15,15</td>
<td>21,9</td>
<td>15,98</td>
<td>17,4</td>
</tr>
<tr>
<td>5</td>
<td>15,62</td>
<td>20,95</td>
<td>15,91</td>
<td>20,63</td>
</tr>
<tr>
<td>6</td>
<td>15,63</td>
<td>20,63</td>
<td>15,76</td>
<td>20,55</td>
</tr>
<tr>
<td>7</td>
<td>15,65</td>
<td>20,53</td>
<td>16,07</td>
<td>20,29</td>
</tr>
<tr>
<td>8</td>
<td>15,94</td>
<td>20,29</td>
<td>16,19</td>
<td>20,81</td>
</tr>
<tr>
<td>9</td>
<td>15,11</td>
<td>16,43</td>
<td>20,81&lt;sup&gt;9&lt;/sup&gt;</td>
<td>15,9</td>
</tr>
<tr>
<td>10</td>
<td>14,94</td>
<td>21,94</td>
<td>16,02</td>
<td>17,17</td>
</tr>
<tr>
<td>11</td>
<td>15,06</td>
<td>20,62</td>
<td>15,27</td>
<td>18,58</td>
</tr>
<tr>
<td>12</td>
<td>13,6</td>
<td>18,58</td>
<td>14,16</td>
<td>12,29</td>
</tr>
</tbody>
</table>

**HORIZONTAL LOADS**

Load: 1,11 kN/m²

Measures: 8,384 x 7,53 m²

Hand calculations:

\[
1,11 \frac{kN}{m^2} \cdot 8,384 \, m \cdot 7,53 \, m = 70,08 \, kN
\]

FEM-Design:

Table A.2.12 Results of FEM-Design for the horizontal loads.

<table>
<thead>
<tr>
<th>Lineal distribution (kN)</th>
<th>Original distribution (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70,09</td>
<td>99,10</td>
</tr>
</tbody>
</table>

<sup>9</sup> This wall has two values because one of them corresponds to the wall that excels the building
APPENDIX 3. MODULUS OF ELASTICITY FOR TRÄ8 ELEMENTS

A3. 1 Stabilisation wall

The wall can be divided in two different parts: glulam and LVL. The measures of these parts are:

\[ b_g = 160 \, \text{mm} \]

\[ h_{gl} = 560 \, \text{mm} \]

\[ h_{g2} = 225 \, \text{mm} \]

\[ t_e = 27 \, \text{mm} \]

\[ h_L = 2400 \, \text{mm} \]

where \( g \) is equal to glulam and \( L \) is equal to LVL

\[ E_{g\text{mean}} = 12600 \, \text{N/mm}^2 \]

\[ E_{LVL\text{mean}} = 10500 \, \text{N/mm}^2 \]

And using the following equation \( EI_{\text{TOTAL}} \) can be obtained (Eq A3.1):

\[ EI = E_g \left( \frac{b_g h_g^3}{12} + 2 \left( \frac{b_g h_{g1}^3}{12} + b_g h_g \left( \frac{h_k}{2} - \frac{h_{g1}}{2} \right)^3 \right) \right) + E_L 2 \frac{t_e h_k^3}{12} \]

\[ EI_{\text{TOTAL}} = 2,18 \times 10^{15} \, \text{Nmm}^2 \]

Later a length and a load had to be chosen. In this case is going to be used \( L = 6000 \, \text{mm} \) and \( F = 100000 \, \text{N} \).

Knowing that \( (EI)_{\text{TOTAL}} = EI \) the following equation is used:

\[ u_{\text{bend}} = \frac{F L^3}{3EI} \tag{A3.2} \]

\[ u_{\text{bend}} = 3.30 \, \text{mm} \]

If the composite wall is going to be substituted by a timber wall which has to have the same elastic behaviour, its displacement will be the same, hence:
b’ = 214 mm
h’ = 2400 mm

\[ I' = \frac{ph^3}{12} = 2.47 \cdot 10^{11} \text{ mm}^4 \]  
(A3.3)

\[ E' = \frac{Ft^3}{3I' \mu_{bend}} = 8846.60 \text{ N/mm}^2 \]  
(A3.4)

\[ E_{0.05} = 8042.37 \text{ N/mm}^2 \]

**A3.2 Floor**

To be able to define floor in FEM Design, it needs to be represented by the solid section. To calculate the modulus of elasticity of the substitute floor, a simply supported beam is considered with a given section.

This piece of floor can be divided in 3 different parts. One made of Kerto Q and another one made of Kerto S. The measures of these parts are:

b₁ = 600 mm
h₁ = 27 mm
b₂ = 39 mm
h₂ = 360 mm
b₃ = 300 mm
h₃ = 39 mm

With the measures it is possible to calculate the moment of inertia, but first it is necessary to find the position of the neutral axis. This is going to be found by solving the following equation for static moment:

\[ S_x = 0 \]

\[ S_x = b_1 h_1 \left( y - \frac{h_1}{2} \right) + b_2 h_2 \left( h_1 + \frac{h_2}{2} - y \right) + b_3 h_3 \left( h_1 + h_2 + \frac{h_3}{2} - y \right) = 0 \]  
(A3.5)
Then it is found $y = 438.93 \, mm$ and with this value is possible to find the value of the moment of inertia:

$$I_1 = \frac{b_1 h_1^3}{12} + b_1 h_1 \left( y - \frac{h_1}{2} \right)^2 = 2.93 \cdot 10^8 \, mm^4$$  \hspace{1cm} (A3.6)

$$I_2 = \frac{b_2 h_2^3}{12} + b_2 b_2 \left( h_1 + \frac{h_2}{2} - y \right)^2 = 9.07 \cdot 10^8 \, mm^4$$  \hspace{1cm} (A3.7)

$$I_3 = \frac{b_3 h_3^3}{12} + b_3 h_3 \left( h_1 + h_2 + \frac{h_3}{2} - y \right)^2 = 1.38 \cdot 10^7 \, mm^4$$  \hspace{1cm} (A3.8)

$$EI = E_1 I_1 + E_2 I_2 + E_3 I_3 = 3.65 \cdot 10^{13} \, N \cdot mm^2$$  \hspace{1cm} (A3.9)

The assumed simply supported beam has length $L = 1000 \, mm$ and is loaded with equally distributed load $q = 5000 \, N/mm$.

The maximum deflection of considered beam is in the middle of its length and is expressed by the following formula:

$$u_{bend} = \frac{5 \cdot q l^4}{384 \cdot EI}$$  \hspace{1cm} (A3.10)

$$u_{bend} = 1.78 \, mm$$

If the composite floor is going to be substituted by a solid timber floor which has to have the same elastic behaviour, its displacement will be the same, hence:

$b' = 600 \, mm$

$h' = 426 \, mm$

$$I' = \frac{b h^3}{12} = 3.87 \cdot 10^8 \, mm^4$$  \hspace{1cm} (A3.11)

$$E' = \frac{5 \cdot q l^4}{384 \cdot I' u_{bend}} = 9440 \, N/mm^2$$  \hspace{1cm} (A3.12)

To be able to define the floor in FEM Design, a simplifying assumption can be taken that:

$$E_{0.05} = 8581.82 \, N/mm^2$$
APPENDIX 4. RESULTS OF FEM DESIGN

Here is going to be given the solution of the equation that FEM Design uses in order to achieve the necessary section. The case 1 is only with one trá8 floor and the case 2 is with two trá8 floors.

BUILDING WITH COLUMNS

Case 1

B.7
Maximum of load combinations

Rectangle 215x1350
GL 32c (Glued laminated), Service class: 3, \(\gamma_M = 1.30\), \(k_{sys} = 1.00\)

\[
\begin{align*}
A &= 290250 \text{ mm}^2 \\
W_1 &= 6.531 \times 10^7 \text{ mm}^3 \\
W_2 &= 1.040 \times 10^7 \text{ mm}^3 \\
i_1 &= 390 \text{ mm} \\
i_2 &= 62 \text{ mm} \\
l_1 &= 1.118 \times 10^9 \text{ mm}^4 \\
l_2 &= 4.023 \times 10^9 \text{ mm}^4
\end{align*}
\]

Combined bending and axial tension - 6.2.3
LC: ULS1 (\(k_{mod} = 0.90\)), \(x = 1734 \text{ mm}\)

\[
\frac{\sigma_{t,d}}{f_{t,d}} + \frac{\sigma_{w,d}}{f_{w,d}} + k_m \frac{\sigma_{m,d}}{f_{m,d}} = \frac{0.00}{15.50} + \frac{0.44}{22.15} + \frac{0.7}{24.37} = 0.02 \leq 1 \quad (6.17) - \text{OK}
\]

\[
\frac{\sigma_{t,d}}{f_{t,d}} + k_m \frac{\sigma_{m,d}}{f_{m,d}} = \frac{0.00}{15.50} + \frac{0.44}{22.15} = 0.01 \leq 1 \quad (6.18) - \text{OK}
\]

Combined bending and axial compression - 6.1.4, 6.2.4
LC: ULS7 (\(k_{mod} = 0.90\)), \(x = 1734 \text{ mm}\)

\[
\left(\frac{\sigma_{t,d}}{f_{t,d}}\right)^2 + \frac{\sigma_{m,d}}{f_{m,d}} + k_m \frac{\sigma_{m,d}}{f_{m,d}} = \left(\frac{0.49}{18.35}\right)^2 + \frac{16.83}{22.15} + 0.7 \frac{0.26}{24.37} = 0.77 \leq 1 \quad (6.19) - \text{OK}
\]

\[
\left(\frac{\sigma_{t,d}}{f_{t,d}}\right)^2 + k_m \frac{\sigma_{m,d}}{f_{m,d}} = \left(\frac{0.49}{18.35}\right)^2 + 0.7 \frac{16.83}{22.15} + 0.26 = 0.54 \leq 1 \quad (6.20) - \text{OK}
\]
Combined shear and torsion - 6.1.7, 6.1.8

LC: ULS7 ($k_{mod} = 0.90$), $x = 1734$ mm

$\tau_{d} = 4.65 \text{ N/mm}^2 \geq f_{u,d} = 2.22 \text{ N/mm}^2$ \hspace{1cm} (6.13) - Not OK

Flexural buckling around axis 1 - 6.3.2

LC: ULS7 ($k_{mod} = 0.90$), $x = 1734$ mm

$\beta_{e} = 0.1$ \hspace{1cm} (6.29)

$L_{rel,1} = \frac{1}{1 + \beta_{e} (\lambda_{rel,1} \cdot 0.3) + \lambda_{rel,1}^2} = 0.5 (1 + 0.1 (0.300 \cdot 0.3) + 0.300^2) = 0.545$ \hspace{1cm} (6.27)

$k_{c,1} = 1 - \frac{1}{k_{1} + \sqrt{k_{1}^2 - \lambda_{rel,1}^2}} = 1.000$ \hspace{1cm} (6.25)

$k_{m,1,d} = \frac{\sigma_{m,1,d}}{k_{c,1}} = \frac{0.49 + \sqrt{0.49^2 - 0.300^2}}{1.000 - 0.1835 \times 22.15 + 0.7 + 24.37}$ = 0.79 \leq 1 \hspace{1cm} (6.23) - OK

Flexural buckling around axis 2 - 6.3.2

LC: ULS7 ($k_{mod} = 0.90$), $x = 1734$ mm

$\beta_{e} = 0.1$ \hspace{1cm} (6.29)

$L_{rel,2} = \frac{1}{1 + \beta_{e} (\lambda_{rel,2} \cdot 0.3) + \lambda_{rel,2}^2} = 0.5 (1 + 0.1 (0.435 \cdot 0.3) + 0.435^2) = 0.601$ \hspace{1cm} (6.28)

$k_{c,2} = 1 - \frac{1}{k_{2} + \sqrt{k_{2}^2 - \lambda_{rel,2}^2}} = 0.984$ \hspace{1cm} (6.26)

$k_{m,2,d} = \frac{\sigma_{m,2,d}}{k_{c,2}} = \frac{0.49 + \sqrt{0.49^2 - 0.435^2}}{0.984 - 0.1835 \times 22.15 + 0.7 + 24.37} = 0.57 \leq 1 \hspace{1cm} (6.24) - OK

Lateral torsional buckling - 6.3.3

LC: ULS7 ($k_{mod} = 0.90$), $x = 1734$ mm

$W_{ef} = 1 \cdot f_{\tau} \left( \frac{12.5 M_{\max}}{2.5 M_{\max} + 5 M_{y} + 3 M_{z}} \right)^1 \cdot 0.5 h$ $= 1 \cdot 0.5 h$

$W_{ef} = 1 \cdot f_{\tau} \left( \frac{12.5 \times 1098.72 + 3 \times 17.66 + 4 \times 349.04 + 3 \times 708.06}{1734 \cdot 0.5 \cdot 1350} \right) = 1350 \text{ mm}^2$

$\sigma_{m,\text{eff}} = \frac{\sqrt{\frac{\pi}{4}} \cdot 3.14 \cdot 1.118 \cdot 0.994 \cdot 4.923e+09}{123 \cdot 6.531e+07} = 2302.82 \text{ N/mm}^2$ \hspace{1cm} (6.31)

$\lambda_{rel,m} = \frac{1682}{\sigma_{m,\text{eff}} \cdot 2302.82} = 0.118$ \hspace{1cm} (6.30)

$\lambda_{rel,m} \leq 3.75$, $\kappa_{ef} = 1.0$ \hspace{1cm} (6.34)

$k_{c,1,m,1,d} = \frac{1682}{1000 - 22.15} = 0.76 \leq 1$ \hspace{1cm} (6.33) - OK

$k_{c,2,m,1,d} = \frac{1682}{1000 - 22.15} = 0.76 \leq 1$ \hspace{1cm} (6.33) - OK

$\left( \frac{\sigma_{m,1,d}}{k_{c,1,m,1,d}} \right) ^2 + \left( \frac{\sigma_{o,1,d}}{k_{c,2,m,1,d}} \right) ^2 = 0.49 + 0.984 \leq 1$ \hspace{1cm} (6.35) - OK
Case 2

B.14
Maximum of load combinations

Rectangle 215x1350
GL 32c (Glued laminated), Service class: 3, $\gamma_M = 1.30$, $k_{sys} = 1.00$

\[
\begin{align*}
A &= 290250 \text{ mm}^2 & E_{p,05} &= 11100 \text{ N/mm}^2 \\
W_1 &= 6.531e+07 \text{ mm}^3 & G_{p,05} &= 694 \text{ N/mm}^2 \\
W_2 &= 1.040e+07 \text{ mm}^3 & f_{t,0,k} &= 19.50 \text{ N/mm}^2 \\
i_1 &= 390 \text{ mm} & f_{p,0,k} &= 26.50 \text{ N/mm}^2 \\
i_2 &= 62 \text{ mm} & f_{m,1,k} &= 32.00 \text{ N/mm}^2 \\
i_3 &= 1.116e+09 \text{ mm}^4 & f_{m,2,k} &= 35.20 \text{ N/mm}^2 \\
i_4 &= 4.023e+09 \text{ mm}^4 & f_{v,k} &= 3.20 \text{ N/mm}^2 \\
\end{align*}
\]

Combined bending and axial tension - 6.2.3
LC: ULSS ($k_{mod} = 0.90$), $x = 0 \text{ mm}$

\[
\begin{align*}
\frac{\sigma_{t,0,d}}{f_{c,d}} + \frac{\sigma_{m,1,d} + k_m \sigma_{m,2,d}}{f_{m,1,d}} &= \frac{0.02}{13.90} + \frac{0.04}{24.37} = 0.03 \leq 1 \quad (6.17) \quad \text{- OK} \\
\frac{\sigma_{t,0,d} + k_m \sigma_{m,1,d} + k_m \sigma_{m,2,d}}{f_{m,1,d}} &= \frac{0.02}{13.90} + \frac{0.04}{24.37} = 0.02 \leq 1 \quad (6.18) \quad \text{- OK}
\end{align*}
\]

Combined bending and axial compression - 6.1.4, 6.2.4
LC: ULSS ($k_{mod} = 0.90$), $x = 0 \text{ mm}$

\[
\begin{align*}
\sigma_{c,d} &= 0.30 \text{ N/mm}^2 \leq f_{c,d} = 18.35 \text{ N/mm}^2 \quad (6.2) \quad \text{- OK} \\
\left(\frac{\sigma_{t,0,d}}{f_{c,d}} + \frac{\sigma_{m,1,d} + k_m \sigma_{m,2,d}}{f_{m,1,d}}\right)^2 &= \left(\frac{0.30}{18.35}\right)^2 + \frac{7.27}{22.15} + \frac{0.13}{24.37} = 0.33 \leq 1 \quad (6.19) \quad \text{- OK} \\
\left(\frac{\sigma_{t,0,d}}{f_{c,d}} + k_m \sigma_{m,1,d} + k_m \sigma_{m,2,d}\right)^2 &= \left(\frac{0.30}{18.35}\right)^2 + \frac{7.27}{22.15} + \frac{0.13}{24.37} = 0.24 \leq 1 \quad (6.20) \quad \text{- OK}
\end{align*}
\]
Combined shear and torsion - 6.1.7, 6.1.8
LC: ULS7 ($k_{mod} = 0.90$), $x = 0$ mm

$\tau_d = 2.48 \text{ N/mm}^2 > f_{\tau,d} = 2.22 \text{ N/mm}^2$ \hspace{1em} (6.13) \hspace{1em} - Not OK

Flexural buckling around axis 1 - 6.3.2
LC: ULS7 ($k_{mod} = 0.90$), $x = 0$ mm

$\beta_e = 0.1$ \hspace{1em} (6.29)

$\lambda_{rel,1} = \frac{\lambda_{k1}}{\lambda_{E,0.05}} = \frac{4.45}{3.14 \cdot 11100} = 0.300$ \hspace{1em} (6.21)

$k_1 = 0.5 \left( 1 + \beta_e (\lambda_{rel,1} - 0.3) + \lambda_{rel,1}^2 \right) = 0.5 \left( 1 + 0.1(0.300 - 0.3) + 0.300^2 \right) = 0.545$ \hspace{1em} (6.27)

$k_e,1 = \frac{1}{k_1 + \sqrt{k_1^2 - \lambda_{rel,1}^2}} = \frac{1}{0.545 + \sqrt{0.545^2 - 0.300^2}} = 1.000$ \hspace{1em} (6.25)

$\frac{\sigma_{0,0,d}}{k_e,1 \cdot f_{c,0,d}} + \frac{\sigma_{m,1,d}}{k_m \cdot f_{m,1,d}} + \frac{\sigma_{m,2,d}}{k_m \cdot f_{m,2,d}} = \frac{0.30}{1.000 \cdot 18.35} + \frac{7.27}{22.15} + \frac{0.13}{24.37} = 0.36 \leq 1$ \hspace{1em} (6.23) \hspace{1em} - OK

Flexural buckling around axis 2 - 6.3.2
LC: ULS7 ($k_{mod} = 0.90$), $x = 0$ mm

$\beta_e = 0.1$ \hspace{1em} (6.29)

$\lambda_{rel,2} = \frac{\lambda_{k2}}{\lambda_{E,0.05}} = \frac{27.94}{3.14 \cdot 11100} = 0.343$ \hspace{1em} (6.22)

$k_2 = 0.5 \left( 1 + \beta_e (\lambda_{rel,2} - 0.3) + \lambda_{rel,2}^2 \right) = 0.5 \left( 1 + 0.1(0.343 - 0.3) + 0.343^2 \right) = 0.601$ \hspace{1em} (6.28)

$k_e,2 = \frac{1}{k_2 + \sqrt{k_2^2 - \lambda_{rel,2}^2}} = \frac{1}{0.601 + \sqrt{0.601^2 - 0.343^2}} = 0.984$ \hspace{1em} (6.26)

$\frac{\sigma_{0,0,d}}{k_e,2 \cdot f_{c,0,d}} + \frac{\sigma_{m,1,d}}{k_m \cdot f_{m,1,d}} + \frac{\sigma_{m,2,d}}{k_m \cdot f_{m,2,d}} = \frac{0.30}{0.984 \cdot 18.35} + \frac{7.27}{22.15} + \frac{0.13}{24.37} = 0.26 \leq 1$ \hspace{1em} (6.24) \hspace{1em} - OK

Lateral torsional buckling - 6.3.3
LC: ULS7 ($k_{mod} = 0.90$), $x = 0$ mm

$\lambda_{ref} = \frac{12.5 \cdot M_{max}}{2.5 \cdot M_{max} + 3M_2 + 4M_3 + 3M_4} \cdot 0.5h$ \hspace{1em} (6.29)

$\lambda_{ref} = \frac{12.5 \cdot 474.85}{2.5 \cdot 474.85 + 3 \cdot 268.93 + 4 \cdot 72.14 + 3 \cdot 122.37} \cdot 0.5 \cdot 1350 = 99$ mm

$\sigma_{m, crit} = \tau_{crit} = \frac{m_{rel, k}}{\sigma_{m, crit}} = \frac{3.14 \cdot 11100 \cdot 1.118 \cdot 0.9 \cdot 694 \cdot 4.023 \cdot 0.9}{99 \cdot 6.631 \cdot 0.07} = 2658.85 \text{ N/mm}^2$ \hspace{1em} (6.31)

$\lambda_{rel, m} = \frac{\lambda_{ref, k}}{\sigma_{m, crit}} = \frac{32.00}{2658.85} = 0.120$ \hspace{1em} (6.30)

$k_{rel, m} = 0.75$, $k_{crit} = 1.0$ \hspace{1em} (6.34)

$\frac{\sigma_{m, 1,d}}{k_{rel, m, 1,d}} = \frac{7.27}{1.000 \cdot 22.15} = 0.33 \leq 1$ \hspace{1em} (6.33) \hspace{1em} - OK

$\frac{\sigma_{0,0,d}}{k_{rel, m, 1,d}} = \frac{0.30}{1.000 \cdot 22.15} = 0.12 \leq 1$ \hspace{1em} (6.35) \hspace{1em} - OK
B.7
Maximum of load combinations

Rectangle 215x1350
GL 32c (Glued laminated), Service class: 3, \( \gamma_M = 1.30 \), \( k_{yz} = 1.00 \)

\[
\begin{align*}
A &= 290250 \text{ mm}^2 \quad E_{\sigma,0} = 11100 \text{ N/mm}^2 \\
W_t &= 6.531 \times 10^7 \text{ mm}^3 \quad G_{\sigma,0} = 694 \text{ N/mm}^2 \\
W_b &= 1.040 \times 10^7 \text{ mm}^3 \quad t_{b,k} = 19.50 \text{ N/mm}^2 \\
i_1 &= 390 \text{ mm} \quad t_{b,b,k} = 26.50 \text{ N/mm}^2 \\
i_2 &= 62 \text{ mm} \quad t_{m,1,k} = 32.00 \text{ N/mm}^2 \\
i_3 &= 1.118 \times 10^9 \text{ mm}^4 \quad t_{m,2,k} = 35.20 \text{ N/mm}^2 \\
i_4 &= 4.023 \times 10^9 \text{ mm}^4 \quad t_{v,k} = 3.20 \text{ N/mm}^2 \\
\end{align*}
\]

**Combined bending and axial tension - 6.2.3**

\[
\frac{\sigma_{b,d}}{t_{b,b,k}} + \frac{\sigma_{m,1,d}}{t_{m,1,k}} + \frac{\sigma_{m,2,d}}{t_{m,2,k}} = 0.02 + 0.40 + 0.7 = 1.12 < 1 \quad (6.17) \quad \text{OK}
\]

**Combined bending and axial compression - 6.1.4, 6.2.4**

\[
\frac{\sigma_{c,b,d}}{t_{b,b,k}} + \frac{\sigma_{m,1,d}}{t_{m,1,k}} + \frac{\sigma_{m,2,d}}{t_{m,2,k}} = 0.02 + 0.40 + 0.7 = 1.12 < 1 \quad (6.18) \quad \text{OK}
\]

\[
\frac{(\sigma_{c,b,d})^2}{t_{b,b,k}^2} + \frac{\sigma_{m,1,d}^2}{t_{m,1,k}^2} + \frac{\sigma_{m,2,d}^2}{t_{m,2,k}^2} = \left(0.18^2\right) + 10.72 + 0.7 = 11.31 > 1 \quad (6.19) \quad \text{OK}
\]

\[
\frac{(\sigma_{c,b,d})^2}{t_{b,b,k}^2} + \frac{\sigma_{m,1,d}^2}{t_{m,1,k}^2} + \frac{\sigma_{m,2,d}^2}{t_{m,2,k}^2} = \left(0.18^2\right) + 10.72 + 0.7 = 11.31 > 1 \quad (6.20) \quad \text{OK}
\]
Combined shear and torsion - 6.1.7, 6.1.8
LC: ULS7 (\(k_{mod} = 0.90\)), \(x = 1734\) mm
\(t_d = 3.68\) N/mm\(^2\) > \(f_{c,d} = 2.22\) N/mm\(^2\) \((6.13)\) - Not OK

Flexural buckling around axis 1 - 6.3.2
LC: ULS7 (\(k_{mod} = 0.90\)), \(x = 1734\) mm
\(\beta_0 = 0.1\) \((6.29)\)
\(\lambda_{rel,1} = \frac{\lambda_1}{\sqrt{\frac{E_{fl,0.05}}{E_{fl,0.05}}} = \frac{4.45 \cdot 26.50}{3.14 \cdot \sqrt{11100}} = 0.300\) \((6.21)\)
\(k_1 = 0.5\left(1 + \beta_0(\lambda_{rel,1} - 0.3) + \lambda_{rel,1}^2\right) = 0.5\left(1 + 0.1(0.300 - 0.3) + 0.300^2\right) = 0.545\) \((6.27)\)
\(k_{o,1} = \frac{1}{k_1 + \sqrt{k_1^2 - \lambda_{rel,1}^2}} = \frac{1}{0.545 + \sqrt{0.545^2 - 0.300^2}} = 1.000\) \((6.25)\)
\(\frac{\sigma_{c,1,d}}{k_{o,1}} \frac{\tau_{m,1,d}}{t_{m,1,d}} + \frac{\sigma_{m,2,d}}{k_{o,2}} \frac{\tau_{m,2,d}}{t_{m,2,d}} = \frac{0.18}{1.000 \cdot 18.35} + \frac{10.72}{22.15} + 0.7 = 0.12 \in [0.5 \leq 1\) \((6.23)\) - OK

Flexural buckling around axis 2 - 6.3.2
LC: ULS7 (\(k_{mod} = 0.90\)), \(x = 1734\) mm
\(\beta_0 = 0.1\) \((6.29)\)
\(\lambda_{rel,2} = \frac{\lambda_2}{\sqrt{\frac{E_{fl,0.05}}{E_{fl,0.05}}} = \frac{27.94 \cdot 26.50}{3.14 \cdot \sqrt{11100}} = 0.436\) \((6.22)\)
\(k_2 = 0.5\left(1 + \beta_0(\lambda_{rel,2} - 0.3) + \lambda_{rel,2}^2\right) = 0.5\left(1 + 0.1(0.436 - 0.3) + 0.436^2\right) = 0.601\) \((6.28)\)
\(k_{o,2} = \frac{1}{k_2 + \sqrt{k_2^2 - \lambda_{rel,2}^2}} = \frac{1}{0.601 + \sqrt{0.601^2 - 0.436^2}} = 0.904\) \((6.26)\)
\(\frac{\sigma_{c,2,d}}{k_{o,2}} \frac{\tau_{m,2,d}}{t_{m,2,d}} = \frac{0.18}{0.904 \cdot 18.35} + \frac{10.72}{22.15} + 0.7 = 0.12 \in [0.35 \leq 1\) \((6.24)\) - OK

Lateral torsional buckling - 6.3.3
LC: ULS7 (\(k_{mod} = 0.90\)), \(x = 1734\) mm
\(I_{ef} = 1 / \left(\frac{12.5M_{Max}}{2.5M_{Max} + 3M_2 + 4M_3 + 3M_4}\right) \cdot 1 \cdot 0.5h\)
\(I_{ef} = 1 / \left(\frac{12.5 \cdot 700.33 + 3 \cdot 49.87 + 4 \cdot 154.78 + 3 \cdot 396.89}{60 \cdot 6.531 + 0.7}\right) = 1734 \cdot 0.5 \cdot 1350 = 60\) mm
\(\sigma_{m,crk} = \frac{\sqrt{E_{fl,0.05} \lambda_{rel,2}}}{I_{fl,0.05}} = \frac{3.14 \cdot \sqrt{11100 \cdot 0.082 \cdot 694 \cdot 4 \cdot 0.23 + 0.09}}{60 \cdot 6.531 + 0.7} = 4725.98\) N/mm\(^2\) \((6.31)\)
\(\lambda_{rel,m} = \sqrt{\frac{I_{fl,1,k}}{\sigma_{m,crk}}} = \sqrt{32.00 / 4725.98} = 0.082\) \((6.30)\)
\(\lambda_{rel,m} \leq 0.75\), \(k_{crk} = 1.0\) \((6.34)\)
\(\frac{\sigma_{m,1,d}}{k_{crk}} \frac{\tau_{m,1,d}}{t_{m,1,d}} = \frac{10.72}{1000 \cdot 22.15} = 0.48 \leq 1\) \((6.33)\) - OK
\(\left(\frac{\sigma_{m,1,d}}{k_{crk}} \frac{\tau_{m,1,d}}{t_{m,1,d}}\right)^2 + \left(\frac{\sigma_{c,1,d}}{k_{crk}} + \frac{\tau_{c,1,d}}{t_{m,1,d}}\right)^2 = \frac{10.72}{0.18} + 0.18 \leq 1\) \((6.35)\) - OK
B.39
Maximum of load combinations

Rectangle 215x180
GL 32c (Glued laminated), Service class: 3, \( V_m = 1.30 \), \( k_{sys} = 1.00 \)

\[
\begin{align*}
A &= 38700 \text{ mm}^2 & \varepsilon_{0,05} &= 11100 \text{ N/mm}^2 \\
W_1 &= 1.387 \times 10^6 \text{ mm}^3 & C_{0,6} &= 694 \text{ N/mm}^2 \\
W_2 &= 1.161 \times 10^6 \text{ mm}^3 & \varepsilon_{0,k} &= 21.45 \text{ N/mm}^2 \\
l_1 &= 62 \text{ mm} & f_{0,k} &= 26.50 \text{ N/mm}^2 \\
l_2 &= 52 \text{ mm} & f_{m,1,k} &= 35.20 \text{ N/mm}^2 \\
l_2 &= 1.045 \times 10^8 \text{ mm}^4 & f_{m,2,k} &= 35.20 \text{ N/mm}^2 \\
l_4 &= 2.075 \times 10^8 \text{ mm}^4 & f_{v,k} &= 3.20 \text{ N/mm}^2 \\
C_{0,6} &= 694 \text{ N/mm}^2 & \varepsilon_{0,05} &= 11100 \text{ N/mm}^2 \\
W_1 &= 1.387 \times 10^6 \text{ mm}^3 & C_{0,6} &= 694 \text{ N/mm}^2 \\
W_2 &= 1.161 \times 10^6 \text{ mm}^3 & \varepsilon_{0,k} &= 21.45 \text{ N/mm}^2 \\
l_1 &= 62 \text{ mm} & f_{0,k} &= 26.50 \text{ N/mm}^2 \\
l_2 &= 52 \text{ mm} & f_{m,1,k} &= 35.20 \text{ N/mm}^2 \\
l_2 &= 1.045 \times 10^8 \text{ mm}^4 & f_{m,2,k} &= 35.20 \text{ N/mm}^2 \\
l_4 &= 2.075 \times 10^8 \text{ mm}^4 & f_{v,k} &= 3.20 \text{ N/mm}^2 \\
\end{align*}
\]

Combined bending and axial tension - 6.2.3

LC: ULS1 \( (f_{mod} = 0.90) \), \( x = 434 \text{ mm} \)

\[
\frac{\sigma_{0,d}}{f_{0,d}} + \frac{\sigma_{m,1,d}}{f_{m,1,d}} + \frac{\sigma_{m,2,d}}{f_{m,2,d}} = \frac{0.17}{14.95} + \frac{0.12}{24.37} + 0.7 \frac{1.30}{24.37} = 0.05 \leq 1 \quad (6.17) \quad \text{OK}
\]

Combined bending and axial compression - 6.1.4, 6.2.4

LC: ULS7 \( (f_{mod} = 0.90) \), \( x = 1734 \text{ mm} \)

\[
\frac{\sigma_{0,d}}{f_{0,d}} = 1.27 \text{ N/mm}^2 \leq f_{c,d} = 18.35 \text{ N/mm}^2 \quad (6.2) \quad \text{OK}
\]

\[
\left( \frac{\sigma_{0,d}}{f_{0,d}} \right)^2 + \frac{\sigma_{m,1,d}}{f_{m,1,d}} + \frac{\sigma_{m,2,d}}{f_{m,2,d}} = \left( \frac{1.27}{18.35} \right)^2 + 0.92 + 0.7 \frac{1.30}{24.37} = 0.10 \leq 1 \quad (6.19) \quad \text{OK}
\]

\[
\left( \frac{\sigma_{0,d}}{f_{0,d}} \right)^2 + \frac{\sigma_{m,1,d}}{f_{m,1,d}} + \frac{\sigma_{m,2,d}}{f_{m,2,d}} = \left( \frac{1.27}{18.35} \right)^2 + 0.92 + 0.7 \frac{1.30}{24.37} = 0.12 \leq 1 \quad (6.20) \quad \text{OK}
\]
Combined shear and torsion - 6.1.7, 6.1.8
LC: ULS7 ($\kappa_{\text{mod}} = 0.90$), $x = 1734$ mm
\[ t_d = 1.41 \text{ N/mm}^2 \leq f_{k,d} = 2.22 \text{ N/mm}^2 \] (6.13) - OK

Flexural buckling around axis 1 - 6.3.2
LC: ULS7 ($\kappa_{\text{mod}} = 0.90$), $x = 1734$ mm
$\beta_s = 0.1$ (6.29)
\[ \lambda_{\text{rel},1} = \frac{\lambda_1}{\sqrt{\frac{f_{k,0.0}}{E_{c,0.0}}} = \frac{27.94}{3.14} \sqrt{\frac{26.50}{11100}}} = 0.435 \] (6.21)
\[ k_1 = 0.5(1 + \beta_s(\lambda_{\text{rel},1} - 0.3) + \lambda_{\text{rel},1}^2) = 0.5(1 + 0.1(0.435 - 0.3) + 0.435^2) = 0.601 \] (6.27)
\[ k_{c,1} = \frac{1}{k_1 + \sqrt{k_1^2 - \lambda_{\text{rel},1}^2}} = \frac{1}{0.601 + \sqrt{0.601^2 - 0.435^2}} = 0.984 \] (6.25)
\[ \frac{\sigma_{0.0,d}}{f_{0.0,d}} + \frac{\sigma_{\text{m},1,d}}{f_{\text{m},1,d}} + k_{m} \frac{\sigma_{\text{m},2,d}}{f_{\text{m},2,d}} = \frac{0.127}{0.984} + \frac{0.92}{18.35} + \frac{0.721}{24.37} = 0.17 \leq 1 \] (6.23) - OK

Flexural buckling around axis 2 - 6.3.2
LC: ULS7 ($\kappa_{\text{mod}} = 0.90$), $x = 1734$ mm
$\beta_s = 0.1$ (6.29)
\[ \lambda_{\text{rel},2} = \frac{\lambda_2}{\sqrt{\frac{f_{k,0.0}}{E_{c,0.0}}} = \frac{33.77}{3.14} \sqrt{\frac{26.50}{11100}}} = 0.619 \] (6.22)
\[ k_2 = 0.5(1 + \beta_s(\lambda_{\text{rel},2} - 0.3) + \lambda_{\text{rel},2}^2) = 0.5(1 + 0.1(0.619 - 0.3) + 0.619^2) = 0.646 \] (6.28)
\[ k_{c,2} = \frac{1}{k_2 + \sqrt{k_2^2 - \lambda_{\text{rel},2}^2}} = \frac{1}{0.646 + \sqrt{0.646^2 - 0.519^2}} = 0.971 \] (6.26)
\[ \frac{\sigma_{0.0,d}}{f_{0.0,d}} + k_{m} \frac{\sigma_{\text{m},1,d}}{f_{\text{m},1,d}} + \frac{\sigma_{\text{m},2,d}}{f_{\text{m},2,d}} = \frac{0.127}{0.971} + \frac{0.92}{18.35} + \frac{0.721}{24.37} = 0.18 \leq 1 \] (6.24) - OK
Lateral torsional buckling - 6.3.3
LC: ULS7 ($V_{mod} = 0.90$), $x = 1734$ mm

\[
\begin{align*}
I_{ef} &= 1 \times \left( \frac{12.5M_{\text{max}}}{(2.5M_{\text{max}} + 3M_{2} + 4M_{3} + 3M_{4})} \right) \times (1 + 2h) \\
I_{ef} &= 1 \times \left( \frac{12.5 \times 1.26}{(2.5 \times 1.26 + 3 \times 0.13 + 4 \times 0.19 + 3 \times 0.32)} \right) \times 1734 + 2 \times 215 = 1006 \text{ mm} \\
\sigma_{m,\text{crit}} &= \frac{\pi}{4} \sqrt{\frac{E_{0,\text{eff}}G_{0,\text{eff}}}{k_{w}W_{t}}} \times 3.14 \sqrt{11100 \times 1.045e+08 \times 694 \times 2.075e+08} = 920.28 \text{ N/mm}^2 \quad (6.31)
\end{align*}
\]

\[
\begin{align*}
\lambda_{\text{rel,m}} &= \sqrt{\frac{I_{m,1,\text{x}}}{C_{m,\text{crit}}}} = \sqrt{\frac{32.00}{920.28}} = 0.186 \quad (6.30) \\
\lambda_{\text{rel,m}} &\leq 0.75, \quad k_{\text{eff}} = 1.0 \quad (6.34) \\
\frac{\sigma_{m,1,d}}{k_{\text{eff,m,1},d}} &= \frac{0.92}{1000 \times 24.37} = 0.04 \leq 1 \quad (6.33) \quad \text{- OK} \\
\left( \frac{\sigma_{m,1,d}}{k_{\text{eff,m,1},d}} \right)^2 + \frac{\sigma_{p,1,d}}{k_{o,2,e,1,d}} &= \left( \frac{0.92}{1000 \times 24.37} \right)^2 + 0.971 \times 18.35 = 0.07 \leq 1 \quad (6.35) \quad \text{- OK}
\end{align*}
\]

Summary

Utilization [%]
B.39
Maximum of load combinations

Rectangle 215x180
GL 32c (Glued laminated), Service class: 3, \( \gamma_M = 1.30 \), \( k_{sys} = 1.00 \)

\[
A = 35700 \text{ mm}^2 \quad E_{0.95} = 11100 \text{ N/mm}^2
\]
\[
W_1 = 1.387e+06 \text{ mm}^3 \quad C_{0.06} = 694 \text{ N/mm}^2
\]
\[
W_2 = 1.161e+06 \text{ mm}^3 \quad f_{0,k} = 21.45 \text{ N/mm}^2
\]
\[
i_1 = 62 \text{ mm} \quad f_{c,0,k} = 26.50 \text{ N/mm}^2
\]
\[
i_2 = 52 \text{ mm} \quad f_{m,1,k} = 35.20 \text{ N/mm}^2
\]
\[
l_2 = 1.045e+08 \text{ mm}^4 \quad f_{m,2,k} = 35.20 \text{ N/mm}^2
\]
\[
l_4 = 2.076e+08 \text{ mm}^4 \quad f_{r,k} = 3.20 \text{ N/mm}^2
\]

Combined bending and axial tension - 6.2.3
LC: ULS1 (\( k_{med} = 0.90 \)), \( x = 0 \) mm

\[
\frac{\sigma_{x,0,d}}{f_{x,0,d}} + \frac{\sigma_{m,1,d}}{f_{m,1,d}} + k_m \frac{\sigma_{m,2,d}}{f_{m,2,d}} = 0.01 \cdot \frac{14.85}{24.37} + 0.7 \cdot \frac{0.70}{24.37} = 0.03 \leq 1 \quad (6.17) - \text{OK}
\]

Combined bending and axial compression - 6.1.4, 6.2.4
LC: ULS7 (\( k_{med} = 0.90 \)), \( x = 1734 \) mm

\[
\sigma_{c,0,d} = 2.06 \text{ N/mm}^2 \leq f_{c,0,d} = 18.35 \text{ N/mm}^2 \quad (6.2) - \text{OK}
\]

\[
\left( \frac{\sigma_{c,0,d}}{f_{c,0,d}} + \frac{\sigma_{m,1,d}}{f_{m,1,d}} + k_m \frac{\sigma_{m,2,d}}{f_{m,2,d}} \right) = \left( \frac{2.06}{18.35} \right)^2 + 0.37 + 0.7 \cdot \frac{3.31}{24.37} = 0.12 \leq 1 \quad (6.19) - \text{OK}
\]

\[
\left( \frac{\sigma_{c,0,d}}{f_{c,0,d}} + k_m \frac{\sigma_{m,1,d}}{f_{m,1,d}} + \frac{\sigma_{m,2,d}}{f_{m,2,d}} \right) = \left( \frac{2.06}{18.35} \right)^2 + 0.7 \cdot \frac{0.37}{24.37} + \frac{3.31}{24.37} = 0.16 \leq 1 \quad (6.20) - \text{OK}
\]
Combined shear and torsion - 6.1.7, 6.1.8
LC: ULS7 ($k_{mod} = 0.90$), $x = 1734$ mm

$t_d = 1.96$ N/mm$^2$ ≤ $f_{c,d} = 2.22$ N/mm$^2$ (6.13) - OK

Flexural buckling around axis 1 - 6.3.2
LC: ULS7 ($k_{mod} = 0.90$), $x = 1734$ mm

$\beta_d = 0.1$ (6.29)

$k_{rel,1} = \frac{k_1}{k_2} = \frac{77.94}{21.60} \cdot \frac{21.60}{3.14} = 71100 = 0.435$ (6.21)

$k_1 = 0.5(1 + \beta_d (\lambda_{rel,1} - 0.3) + \lambda_{rel,1}^2) = 0.5(1 + 0.1(0.435 - 0.3) + 0.435^2) = 0.601$ (6.27)

$k_{c,1} = \frac{1}{k_1 + \sqrt{k_1^2 - \lambda_{rel,1}}} = \frac{1}{0.601 + \sqrt{0.601^2 - 0.435^2}} = 0.964$ (6.25)

$k_{c,1} = \frac{\sigma_{c,d}}{\tau_m,1,d} + \frac{\tau_m,1,d}{k_{rel,1}} = 0.964 \frac{2.06}{18.35} + \frac{0.37}{24.37} = 0.22 \leq 1$ (6.23) - OK

Flexural buckling around axis 2 - 6.3.2
LC: ULS7 ($k_{mod} = 0.90$), $x = 1734$ mm

$\beta_d = 0.1$ (6.29)

$k_{rel,2} = \frac{k_2}{k_2} = \frac{33.37}{21.60} \cdot \frac{21.60}{3.14} = 71100 = 0.519$ (6.22)

$k_2 = 0.5(1 + \beta_d (\lambda_{rel,2} - 0.3) + \lambda_{rel,2}^2) = 0.5(1 + 0.1(0.519 - 0.3) + 0.519^2) = 0.646$ (6.23)

$k_{c,2} = \frac{1}{k_2 + \sqrt{k_2^2 - \lambda_{rel,2}}} = \frac{1}{0.646 + \sqrt{0.646^2 - 0.519^2}} = 0.971$ (6.26)

$k_{c,2} = \frac{\sigma_{c,d}}{\tau_m,1,d} + \frac{\tau_m,1,d}{k_{rel,2}} = 0.971 \frac{2.06}{18.35} + \frac{0.37}{24.37} = 0.26 \leq 1$ (6.24) - OK

Lateral torsional buckling - 6.3.3
LC: ULS7 ($k_{mod} = 0.90$), $x = 1734$ mm

$k_{et} = 1 \left( \frac{12.5M_{max}}{2.5M_{max} + 3M_0 + 2M_4 + 4M_2} \right) = 1 + 2h$

$k_{et} = 1 \left( \frac{12.5 \cdot 0.52 + 3 \cdot 0.03 + 4 \cdot 0.02 + 3 \cdot 0.07}{1734 + 2 \cdot 215} = 877 \text{ mm} \right)$

$\sigma_{m,et} = \frac{\sqrt{E_0} \lambda_{rel,1} \sigma_{0,et}}{k_{et} W_t} = \frac{1055.68}{877 \cdot 1.367^{0.06}} = 1.045 \text{ N/mm}^2$ (6.31)

$\lambda_{rel,m} = \sqrt{\frac{\tau_{m,1,k}}{\sigma_{m,et}}} = \frac{0.174}{1.045} = 0.174$ (6.30)

$\lambda_{rel,m} = 0.75$, $k_{et} = 1.0$ (6.34)

$k_{rel,m,1,d} = 0.37$ (6.33) - OK

$\left( \frac{\tau_{m,1,d}}{k_{rel,m,1,d}} \right)^2 + \frac{\sigma_{c,d}}{\tau_{m,1,d}} = \left( \frac{0.37}{0.37} \right)^2 + \frac{2.06}{0.37} = 1.12 \leq 1$ (6.35) - OK
B.26
Maximum of load combinations

Rectangle 215x225
GL 32c (Glued laminated), Service class: 3, \( \gamma_M = 1.30 \), \( \gamma_{sys} = 1.00 \)

\[
A = 48375 \text{ mm}^2 \quad \varepsilon_{0,05} = 11100 \text{ N/mm}^2 \\
W_t = 1.814 \times 10^6 \text{ mm}^3 \quad \varepsilon_{0.05} = 894 \text{ N/mm}^2 \\
W_2 = 1.733 \times 10^6 \text{ mm}^3 \quad f_{\sigma,k} = 21.45 \text{ N/mm}^2 \\
\iota_1 = 65 \text{ mm} \quad f_{\sigma,k} = 26.50 \text{ N/mm}^2 \\
\iota_2 = 62 \text{ mm} \quad f_{m1,k} = 35.20 \text{ N/mm}^2 \\
\iota_3 = 1.083 \times 10^6 \text{ mm}^4 \quad f_{m1,k} = 35.20 \text{ N/mm}^2 \\
\iota_4 = 3.287 \times 10^6 \text{ mm}^4 \quad f_{k} = 3.20 \text{ N/mm}^2
\]

Combined bending and axial tension - 6.2.3
LC: ULS2 (\( \gamma_{mod} = 0.90 \)), \( x = 3936 \text{ mm} \)
\[
\frac{\varepsilon_{0,05}}{\varepsilon_{m1,0,d}} + \frac{\varepsilon_{m1,0,d}}{\varepsilon_{m2,0,d}} = 0.73 + 0.18 = 0.91 \leq 1 \quad (6.17) \quad \text{OK}
\]

Combined bending and axial compression - 6.1.4, 6.2.4
LC: ULS3 (\( \gamma_{mod} = 0.90 \)), \( x = 7892 \text{ mm} \)
\[
\sigma_{0,0,d} = 1.09 \text{ N/mm}^2 \quad \sigma_{0,0,d} = 18.35 \text{ N/mm}^2 \quad (6.2) \quad \text{OK}
\]
\[
\frac{\sigma_{0,0,d}^2}{\varepsilon_{0,0,d}} + \frac{\sigma_{m1,0,d}}{\varepsilon_{m1,0,d}} + \frac{\sigma_{m2,0,d}}{\varepsilon_{m2,0,d}} = \left( \frac{1.09}{18.35} \right)^2 + \frac{6.71}{24.37} + \frac{0.36}{24.37} = 0.29 \leq 1 \quad (6.19) \quad \text{OK}
\]
\[
\frac{\sigma_{0,0,d}^2}{\varepsilon_{0,0,d}} + \frac{\sigma_{m1,0,d}}{\varepsilon_{m1,0,d}} + \frac{\sigma_{m2,0,d}}{\varepsilon_{m2,0,d}} = \left( \frac{1.09}{18.35} \right)^2 + \frac{6.71}{24.37} + \frac{0.36}{24.37} = 0.21 \leq 1 \quad (6.20) \quad \text{OK}
\]
Combined shear and torsion - 6.1.7, 6.1.8
LC: ULS3 (\(k_{\text{mod}} = 0.90\)), \(x = 7892\) mm
\(t_d = 1.81\) N/mm² ≤ \(f_{c,d} = 2.22\) N/mm² (6.13) - OK

Flexural buckling around axis 1 - 6.3.2
LC: ULS3 (\(k_{\text{mod}} = 0.90\)), \(x = 7892\) mm
\(\beta_e = 0.1\) (6.29)
\(\lambda_{\text{rel},1} = \frac{\lambda_1}{\pi \sqrt{E_{50,d}}} = 19.25 \times \sqrt{\frac{26.5}{11100}} = 0.300\) (6.21)
\(k_1 = 0.5(1 + \beta_e (\lambda_{\text{rel},1} \cdot 0.3) + \lambda_{\text{rel},1}^2) = 0.5(1 + 0.1(0.300 \cdot 0.3) + 0.300^2) = 0.545\) (6.27)
\(k_{c,1} = \frac{1}{k_1 + \sqrt{k_1^2 - \lambda_{\text{rel},1}^2}} = \frac{1}{0.545 + \sqrt{0.545^2 - 0.300^2}} = 1.000\) (6.25)
\(\frac{\sigma_{v,0,d}}{k_{c,1} \cdot t_{n,1,d}} + \frac{\sigma_{m,1,d}}{k_{c,1} \cdot t_{m,1,d}} + \frac{\sigma_{m,2,d}}{k_{c,1} \cdot t_{m,2,d}} = \frac{1.08}{1.000 \cdot 18.35} + \frac{6.71}{24.37} + \frac{0.36}{24.37} = 0.34 \leq 1\) (6.23) - OK

Flexural buckling around axis 2 - 6.3.2
LC: ULS3 (\(k_{\text{mod}} = 0.90\)), \(x = 7892\) mm
\(\beta_e = 0.1\) (6.29)
\(\lambda_{\text{rel},2} = \frac{\lambda_2}{\pi \sqrt{E_{50,d}}} = 20.14 \times \sqrt{\frac{26.5}{11100}} = 0.313\) (6.22)
\(k_2 = 0.5(1 + \beta_e (\lambda_{\text{rel},2} \cdot 0.3) + \lambda_{\text{rel},2}^2) = 0.5(1 + 0.1(0.313 \cdot 0.3) + 0.313^2) = 0.550\) (6.28)
\(k_{c,2} = \frac{1}{k_2 + \sqrt{k_2^2 - \lambda_{\text{rel},2}^2}} = \frac{1}{0.550 + \sqrt{0.550^2 - 0.313^2}} = 0.999\) (6.26)
\(\frac{\sigma_{v,0,d}}{k_{c,2} \cdot t_{n,1,d}} + \frac{\sigma_{m,1,d}}{k_{c,2} \cdot t_{m,1,d}} + \frac{\sigma_{m,2,d}}{k_{c,2} \cdot t_{m,2,d}} = \frac{1.08}{0.999 \cdot 18.35} + \frac{6.71}{24.37} + \frac{0.36}{24.37} = 0.27 \leq 1\) (6.24) - OK

Lateral torsional buckling - 6.3.3
LC: ULS3 (\(k_{\text{mod}} = 0.90\)), \(x = 7892\) mm
\(\lambda_t = 1/\left(\frac{12.5M_{\text{max}}}{2.5M_t + 3M_2 + 4M_3 + 3M_4}\right) - 1 + 2h\)
\(\lambda_t = 1/\left(\frac{12.5 \cdot 0.71 + 3 \cdot 0.05 + 4 \cdot 0.02 + 3 \cdot 0.08}{7250}\right) - 1250 + 2 \cdot 225 = 773\) mm
\(\sigma_{m,\text{req}} = \frac{\pi E_{50,d} t_{n,1,d}}{\lambda_t} \cdot \frac{t_{n,1,d}}{t_{m,1,d}} = 3.14 \sqrt{11100} \cdot 1.863e+08 \cdot 0.944 = 1539.25\) N/mm² (6.31)
\(\lambda_{m,\text{req}} = \sqrt{\frac{m_{\text{req}}}{m_{\text{req}}}} = \sqrt{\frac{26.00}{7535.25}} = 0.144\) (6.30)
\(\lambda_{m,\text{req}} \leq 0.5, \quad k_{\text{set}} = 1.0\) (6.34)
\(\frac{\sigma_{m,1,d}}{k_{\text{set}} \cdot t_{m,1,d}} = \frac{6.71}{1.000 \cdot 24.37} = 0.28 \leq 1\) (6.33) - OK
\(\sigma_{m,1,d}^2 + \frac{\sigma_{m,1,d}^2}{k_{\text{set}} \cdot t_{m,1,d}^2} = \left(1.000 \cdot 24.37\right)^2 + \frac{1.09}{18.35} = 0.14 \leq 1\) (6.35) - OK
APPENDIX 5. MATERIAL PROPERTIES

Table A5.1 Properties of glulam [5]  

<table>
<thead>
<tr>
<th></th>
<th>GL 32c</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bending strength</strong></td>
<td></td>
</tr>
<tr>
<td>$f_{m,g,k}$ (N/mm²)</td>
<td>32</td>
</tr>
<tr>
<td><strong>Tension strength</strong></td>
<td></td>
</tr>
<tr>
<td>$f_{t,0,g,k}$ (N/mm²)</td>
<td>19.5</td>
</tr>
<tr>
<td>$f_{t,90,g,k}$ (N/mm²)</td>
<td>0.45</td>
</tr>
<tr>
<td><strong>Compression strength</strong></td>
<td></td>
</tr>
<tr>
<td>$f_{c,0,g,k}$ (N/mm²)</td>
<td>26.5</td>
</tr>
<tr>
<td>$f_{c,90,g,k}$ (N/mm²)</td>
<td>3</td>
</tr>
<tr>
<td><strong>Shear strength</strong></td>
<td></td>
</tr>
<tr>
<td>$f_{v,g,k}$ (N/mm²)</td>
<td>3.2</td>
</tr>
<tr>
<td><strong>Modulus of elasticity</strong></td>
<td></td>
</tr>
<tr>
<td>$E_{0,g,mean}$ (kN/mm²)</td>
<td>13.7</td>
</tr>
<tr>
<td>$E_{0,g,90}$ (kN/mm²)</td>
<td>11.1</td>
</tr>
<tr>
<td>$E_{90,g,mean}$ (kN/mm²)</td>
<td>0.42</td>
</tr>
<tr>
<td><strong>Shear modulus</strong></td>
<td></td>
</tr>
<tr>
<td>$G_{g,mean}$ (kN/mm²)</td>
<td>0.78</td>
</tr>
<tr>
<td><strong>Density $p_{g,k}$ (kg/m³)</strong></td>
<td>410</td>
</tr>
<tr>
<td>Property</td>
<td>Symbol</td>
</tr>
<tr>
<td>------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td><strong>Fifth percentile values</strong></td>
<td></td>
</tr>
<tr>
<td>Bending strength (N/mm²)</td>
<td></td>
</tr>
<tr>
<td>Edgewise (depth 300)</td>
<td>(f_{0.8,\text{edg.e},k})</td>
</tr>
<tr>
<td>Size effect parameter</td>
<td>(s)</td>
</tr>
<tr>
<td>Flatwise along</td>
<td>(f_{m,0,0,\text{flat},l,k})</td>
</tr>
<tr>
<td>Flatwise across</td>
<td>(f_{m,0,\text{flat},l,k})</td>
</tr>
<tr>
<td>Tensile strength (N/mm²)</td>
<td></td>
</tr>
<tr>
<td>Parallel to grain (length 3000 mm)</td>
<td>(f_{0,k})</td>
</tr>
<tr>
<td>Perpendicular to grain</td>
<td>(f_{90,\text{edg.e},k})</td>
</tr>
<tr>
<td><strong>Compressive Strength</strong></td>
<td></td>
</tr>
<tr>
<td>Parallel to grain</td>
<td>(f_{e,0,k})</td>
</tr>
<tr>
<td>Perpendicular to grain</td>
<td>(f_{e,90,\text{edg.e},k})</td>
</tr>
<tr>
<td>Perpendicular to grain</td>
<td>(f_{e,90,\text{flat},l,k})</td>
</tr>
<tr>
<td><strong>Shear strength (N/mm²)</strong></td>
<td></td>
</tr>
<tr>
<td>Edgewise</td>
<td>(f_{0,0,\text{edg.e},k})</td>
</tr>
<tr>
<td>Flatwise</td>
<td>(f_{0,0,\text{flat},l,k})</td>
</tr>
<tr>
<td><strong>Modulus of elasticity</strong></td>
<td></td>
</tr>
<tr>
<td>Parallel to grain along</td>
<td>(E_{0,k})</td>
</tr>
<tr>
<td>Parallel to grain across</td>
<td>(E_{90,\text{edg.e},k})</td>
</tr>
<tr>
<td>Perpendicular to grain</td>
<td>(E_{90,\text{flat},l,k})</td>
</tr>
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<td>Perpendicular to grain</td>
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</tr>
<tr>
<td><strong>Shear modulus (N/mm²)</strong></td>
<td></td>
</tr>
<tr>
<td>Edgewise</td>
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</tr>
<tr>
<td>Density (kg/m³)</td>
<td>(\rho_{k})</td>
</tr>
<tr>
<td><strong>Mean values</strong></td>
<td></td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td></td>
</tr>
<tr>
<td>Parallel to grain along</td>
<td>(E_{0,\text{mean},\text{lt}})</td>
</tr>
<tr>
<td>Parallel to grain across</td>
<td>(E_{0,\text{mean},\text{lt}})</td>
</tr>
<tr>
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