Environmental impact analysis of structural systems for sustainable buildings

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

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Gothenburg, Sweden 2021
www.chalmers.se

Master's thesis ACEX30 2021

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Master's Thesis 2021
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Cover: 3d view of a preschool concept owned by Skanska and later studied in this report.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2021

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Abstract

The construction industry is one of the largest contributors to all global carbon dioxide emissions. This has led to the climate impact being considered among other traditional building requirements such as the load-bearing capacity and the financial aspect. For this reason, there is a generous number of studies that analyze the climate impact generated by individual building materials and complete buildings, especially apartment buildings. However, there is a lack of information regarding the climate impact caused by structural systems and studies that make comparisons among these.

This thesis initially implements an investigation that concludes in four relevant structural systems capable of being used in the construction of future preschool buildings, and that are applicable in the Skanska project *ABCD-preschools*. Those are later on analyzed through appropriate Life Cycle Assessments which in turn produce data that makes it possible to create a simple and effective tool to assess and evaluate structural systems for future buildings.

The results obtained conclude that structural systems contribute to a remarkable share of the total climate impact produced by preschool buildings. The structural systems' climate impact might nevertheless vary depending on the type of structural system that is utilized. This thesis culminates in conclusions and recommendations which function as tools for project developers to simplify the design choices of structural systems regarding their climate impact.

Keywords: Structural System, Climate Impact, Global Warming Potential, Material Choice, Sustainability, Life Cycle Assessment, Innovations, Climate Goals.

Miljöpåverkansanalys av stomsystem för hållbara byggnader
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Sammanfattning

Byggbranschen är en av de största bidragsgivarna till de globala koldioxidutsläppen. Detta har lett till att klimatpåverkan har beaktats bland andra traditionella byggnadskrav som bärförmåga och ekonomi. Av denna anledning finns det ett generöst antal studier som analyserar klimatpåverkan som genereras av enskilda byggmaterial och kompletta byggnader, särskilt för flerbostadshus. Det saknas dock information om klimatpåverkan genererad av stomsystem och studier som gör jämförelser mellan olika system.

Detta examensarbete implementerar inledningsvis en utvärdering som resulterar i fyra relevanta stomsystem vilka kan användas vid konstruktion av framtida förskolebyggnader och som senare kan nyttjas av Skanska-projektet *ABCD-förskolor*. Dessa system analyseras med hjälp av lämpliga livscykelanalyser som i sin tur generar information som gör det möjligt att skapa ett enkelt och effektivt verktyg för att bedöma och utvärdera stomsystem i framtida byggnader.

De erhållna resultaten visar att stomsystem bidrar till en anmärkningsvärd andel av den totala klimatpåverkan som förskolebyggnader producerar. Stomsystemens klimatpåverkan kan ändå variera beroende på vilken typ av stomsystem som används. Denna avhandling kulminerar i slutsatser och rekommendationer som fungerar som verktyg för projektutvecklare för att förenkla valet gällande stomsystem med avseende på deras klimatpåverkan.

Nyckelord: Stomsystem, Klimatpåverkan, Global Uppvärmningspotential (GWP), Materialval, Hållbarhet, Livscykelanalys, Innovationer, Klimatmål.

Acknowledgements

This Master's thesis was initiated by our examiner Ignasi Fernandez from the Division of Structural Engineering and Building Technology at Chalmers University of Technology, and Johan Österberg from Skanska. Firstly, we would like to thank them for their passion about the subject that initiated this thesis, and for all the help and inspiration throughout our work.

We would also like to thank the following people from Skanska: Our supervisor, Elin Eriksson for all helpful feedback and guidance. Sören Börjesson, thank you for being available at all times and for the help regarding dimensioning calculations. Jeanette Sveder Lundin and Fredrik Dahlgren for sharing knowledge about sustainability and climate impact calculations. Lastly, Nicklas Hagervall and Robert Drotz for giving us a chance to be a part of and influence Skanskas project *ABCD-preschools*, and for your input throughout this thesis.

André Bigott and Jens Milesson, Gothenburg, June 2021

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Nomenclature

Abbreviations

BBR	Boverkets building regulations
BIM	Building information model
BTA	Gross total area
CLT	Cross laminated timber
EPD	Environmental product declaration
GDP	Gross domestic product
GWP	Global warming potential
ISO	International organization for standardization
IVA	Royal Swedish Academy of Engineering Sciences
IVL	Swedish Environmental Research Institute
LCA	Life cycle assessment
LVL	Laminated veneer lumber
SiS	Swedish institute for standards
SLS	Serviceability limit state
ULS	Ultimate limit state

Glossary

A_{temp}	Area inside the outer walls heated to at least 10 degrees Celsius
BM	Software for climate impact calculations
Eurocode	European-wide dimensioning rules for load bearing structures
Glulam	Glued laminated timber
Imposed load	Temporary or moving load from furniture, humans etc., that varies dependent on building type
Revit	BIM software
Structural system	Combination of load bearing elements designed to support a construction

Concepts and Descriptions

ABCD-preschools A project developed by Skanska to meet the need of newly build preschools. There are four different concepts: A, B, C and D, which all differ by size and design. There are also possibilities to modify the concepts to meet the prerequisites for each unique location.

carbon dioxide (CO_2) Carbon dioxide is one of the most considerable greenhouse gas. Carbon dioxide is produced by both natural processes as well as the combustion of wood, or fossil fuels as coal or petroleum. The concentration of carbon dioxide in the atmosphere have increased steadily since the industrialization due to human activities. Carbon dioxide dissolves in the ocean and can be stored in organic materials, such as timber, but about 50% of the carbon dioxide released from burning fossil fuels remain in the atmosphere.

carbon dioxide equivalents Carbon dioxide is not the only greenhouse gas that cause climate change, but the most common. Because of this, carbon dioxide equivalents (CO_2-e) are used to calculate the climate impact for all greenhouse gases. The CO_2-equivalents represent the warming potential that any amount of any greenhouse gas has, in relation to the amount of CO_2 needed to warm the earth as much as the original gas.

global warming potential Global warming potential (GWP) is the heat absorbed by the greenhouse gases in the atmosphere. Different gases warming potential can be compared, using their GWP factor. The GWP factor for a greenhouse gas indicates the relation between its warming potential compared to the warming potential of carbon dioxide, and are stated by the unit carbon dioxide equivalents.

life cycle assessment A thorough method, often called LCA, that analyses the cradle-to-grave or cradle-to-cradle life of a commercial product and how it impacts the environment. The aim of this kind of analysis is to improve the environmental character of the products which is partly why its procedures have been standardized by the international organisation of standardisation, ISO.

preliminary sizing Preliminary sizing is a process where dimensions of structural members are roughly estimated using design codes and simplified methods. The preliminary sizes may be refined later on by more detailed processes.

1
Introduction

Sweden along with other countries in the European Union has set up a group of climate goals to be achieved before the year of 2045. One of these goals is to be a fossil-free country (Bengtsson, 2020) and to be one of the first countries in the world to only use renewable energy. Many obstacles have to be tackled to achieve this goal. The environmental impact from the construction sector is one of these obstacles as this impact has been estimated to be 20% of the Swedish total climate impact according to Wärmark, 2020, which is about 11,8 millions carbon dioxide equivalents as reported by Boverket, 2021.The Swedish government has for this reason chosen to start demanding climate declarations for all new buildings (starting on the 1st of January 2022). By doing this, the government is hopeful to speed up the development and increase the all-around knowledge about how the construction of buildings influences the climate change.

The structural system is a substantial part of a building, and a proper choice of structural system is crucial for a building to be both structurally and costly effective. But apart from the structural and economic aspects, there is also the environmental aspect, which is just as important. The choice of structural system will have an impact on the building's environmental footprint either in a negative or positive manner (Nadoushani & Akbarnezhad, 2015).

This thesis will identify, define and quantify the influence that different structural systems have on the climate, specially for a preschool. There are not many significant studies on how influential the structural system is on the climate and neither on how this influence can be estimated when a climate declaration is needed.

1.1 Aim and objective

The structural system stands for a large part of a buildings environmental impact, and is often the largest contributor in the product stage and construction process, as it is concluded in the report written by Liljenström et al., 2015. However, to estimate the magnitude of such impact, a Life Cycle Assessment needs to be carried out individually for each building. The aim of this thesis is then to define an environmental design simplification for different structural solutions, that can be used as a tool to assess the environmental impact of buildings without the need of a LCA. This simplification should act as a guideline and be used by engineers in an early stage of the design process to make appropriate choices for the structural system with regard to environmental impact. Based on this aim, several questions arise and are stated as follows:

- What are the consequences of the choice of structural system regarding the buildings environmental impact?
- How should a system's climate impact be compared to other systems in a simplified but accurate way?
- Can an environmental design factor be used instead of implementing an LCA for each unique project?
- What are the potential improvements regarding material choices for the structural elements that generates the highest climate impact?

The above will be clarified for structural systems that are relevant when building preschools in Sweden. This because there is a lack of information about the climate impact from such buildings, and at the same time that there is a great need to increase the number of preschools being built. According to Skanska, 2021b, there is a desire to build a thousand preschools in Sweden in the coming six years.

1.2 Method

An investigation on the preschool projects performed by Skanska in Sweden under the last years was carried out, where the most common and relevant structural solutions were identified and taken into consideration. A collaboration with the current Skanska project *ABCD-preschools* was established. This led to important information and knowledge about structural systems used in the project, and also about systems that have not been implemented but could be of interest for future preschools. The *ABCD-preschools'* concept C was used as a reference building in the report and has been called reference building and reference system further in the report. The name reference system was used when referring to the building's structural system.

In a first stage, the structural systems was classified and evaluated based on external factors such as economics, structural criteria and production methods. This evaluation acted as a first screening deciding which structural systems that are most of interest to be analysed further.

The next step of the study was to make appropriate Life Cycle Assessments on the previously chosen structural systems using the reference building from the project *ABCD-preschools*. The LCA's results made it possible to identify the reference system's contribution within the whole building's environmental impact as well as climate impact generated by different structural systems. The tools that were used to assemble the LCA of the buildings was Revit to obtain quantity data, and the software BM 1.0 which is a software that is developed by the Swedish Environmental Research Institute, IVL. BM 1.0 consequently uses IVL's generic values and EPD:s to obtain complete results regarding product and construction process stages in an

LCA.

Thereafter, it was achievable to define a simplified method to assess and evaluate the sustainability of the structural systems in future designs. The LCA indicates which elements and parts of the systems' life that have the largest environmental impact. Optimization procedures that can be implemented in an early design stage, and that may reduce the environmental impact were proposed based on the LCA results.

1.3 Scope and limitations

The thesis will study structural systems that have or that could be used to build preschools in Sweden. This choice is made in order to bring more information about emissions and environmental impact from this certain type of building, which is a topic where not many studies have been implemented before. However, the scope of the result can be limited to buildings with similarities to preschools, meaning buildings with comparable sizes and types of use.

No consideration will be taken to the piling and excavations needed to construct the future preschools. The particular reason for this is that different preschools in Sweden will have various foundation solutions where piling might or might not be implemented. These foundations can have a considerable impact on the climate but will not be studied in this report. Additionally, the roof structure and stabilisation of the building will be assumed to be identical for all structural systems for the reason that any change of structural system doesn't need to imply large adjustments on these.

The calculations developed by experts and used by Skanska are simplifications that will make it possible to achieve the aim of the study in the time frame set. The indicator that will be used to describe the environmental impact from the building is GWP (global warming potential). The unit to calculate this impact is kg carbon dioxide equivalents, (CO_2 -equivalents), which compares the relation of any greenhouse gas to carbon dioxide (CO_2) (EuropeanCommission, 2017).

The climate impact from the energy usage of the systems will be calculated by experts at Skanska. The calculations will be performed on the reference building and will be applicable on all structural systems assuming that the systems have the same energy performance. The same procedure applies to the calculations on the climate impact from construction and installation processes of the structures (module A5.2-A5.5 of an LCA).

The chosen analysis period for this study is set to 50 years. The analysis period is proposed by Boverket, 2020 as it is equivalent to the period that other countries in Europe use in their approaches for these types of analyzes. Sub-module B6 will be the only analyzed sub-module from module B since additional sub-modules in B (maintenance, repair, replacement) are not relevant for structural systems during a period of 50 years. Module C, which concerns the systems' end of life will likewise be completely excluded from the life cycle assessment, although their impact will be mentioned and discussed further on.

2
Literature Review

Researchers, companies and governments have been working together for the past decades since it has become general knowledge that the construction industry has an enormous effect on the world's climate. Their goal has been to identify remarkable procedures in the buildings' life cycle so that these can be developed, improved or erased and the climate goals can be achieved. There is a wide variety of literature concerning the climate impact from the construction industry and different projects, but there are not as many studies related to specific parts of the buildings such as the structural system. A number of relevant publications will be summarized and analysed in this chapter.

The article *Climate impact from 60 buildings*, written in Denmark has as an aim to create a sufficient database about the climate impact that Danish buildings stands for during their life cycles. It analyses 60 case buildings in which 11 single-family houses, 12 townhouses, 11 multi-storey dwellings, 22 office buildings and 4 other buildings are included. The report highlights the importance of having a life cycle perspective which entails the impacts that are expected to happen here and now such as production of materials but also the impacts that are assumed to happen in the background of the future life of the buildings, e.g. operational energy, maintenance and demolition (Zimmermann et al., 2020). An illustration of this perspective and the climate impact divided into stages is shown in Figure 2.1 which is provided by the same report.

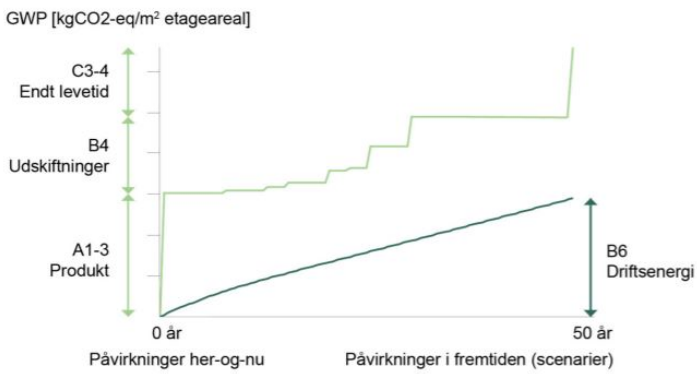

Figure 2.1: *Accumulated climate impact divided into LCA modules. The figure shows both contributions from materials and from operational energy (Zimmermann et al., 2020)*

Reduced climate impact from newly built apartment buildings is a report written by IVL in 2018 and has the purpose to study the climate impact from the entire life cycle of five different construction solutions that are commonly used in the Swedish market for apartment buildings at the moment. The secondary purpose of the report is to investigate if there are possibilities to improve each solution with now-known technology to lower the impact (Erlandsson et al., 2018). The most noteworthy part of this report is the improvements that can be made for each solution depending on the materials and the intention of the solution. The report shows that the systems' climate impact can be significantly reduced between 13% and 21% in every base case if measures are taken (Erlandsson et al., 2018). The solutions studied in this report are the following:

- Complete cast in-situ concrete structure.
- Cast in-situ concrete structure with steel columns.
- Prefabricated concrete structure.
- Volume elements in timber.
- Massive structural system in CLT.

IVL used the same building project to make further investigations in a second report named *The climate impact of construction*. This report studies climate impact and energy use by performing a life cycle assessment for a newly built apartment building. This instead of comparing different materials or different structural systems like in *Reduced climate impact from newly built apartment buildings*. The report aims to produce a detailed example of the climate impact and energy usage linked to the construction process and the usage stage of the building. The author desires to increase the knowledge about how the climate impact and energy usage correlate to the choices made during the construction process and to illustrate an example of how LCA calculations can be performed based on the standards and rules that apply today. Increased awareness for this type of matter is very important to improve the communication and cooperation between different actors in the sector according to Liljenström et al., 2015. To create a reliable database there is still a need to perform similar studies for different types of buildings, buildings constructed with different materials, different environmental impact categories, or more detailed calculations of certain modules in the LCA.

Kurkinen et al., 2015 have studied the climate impact from three different structural systems in Riksbyggen's construction project Viva, in the report *Energy and climate effective building systems*. Viva is a residential quarter with six multi storey apartment buildings. The idea of Viva was to be a sustainable project and to be at the forefront of what is possible with the knowledge and technology available today, which was to result in a fully sustainable residential quarter in ecological, economic and social terms. The results in the report show that there are no significant differences between the three analysed structural solutions, massive CLT system, prefabricated concrete system and cast-in-situ concrete system. This regarding the climate impact as well as primary energy usage in a life cycle perspective. Important to remember regarding the results is that the concrete analysed contains binders with relatively low climate impact. The report highlights the effects that active choices during the construction phase bring to reduce climate impact, like the choice of suppliers with shorter transport distance, and the importance of that the project developer actively make demands regarding material choices and effective construction methods.

Effects of structural system on the life cycle carbon footprint of buildings is a report that has its emphasis on the importance of taking consideration to the entire life cycle carbon footprint when designing the structural systems of future buildings. It is mentioned that the three most important characteristics that are generally analysed in the design phase of a system are the lateral force resistance, the material used and the height of the structure. The report highlights the current lack of knowledge and awareness in the subject and adds that most of the existing literature usually compares a particular structure with two different materials in only a single part of the life cycle instead of studying different frames, materials, heights, and the full life cycle assessment(Nadoushani and Akbarnezhad, 2015). The research highlights the significance of taking consideration to the life cycle footprint when designing a structural system by illustrating the impact that variations in the structural systems might have on the carbon life cycle. It also highlights the relevance of examining the entire life cycle carbon footprint in all its phases instead of only analyzing the emissions from a single phase (Nadoushani and Akbarnezhad, 2015).

Another research entitled *Energy and greenhouse gas emissions associated with the construction of alternative structural systems* written by Raymond J Cole aims to examine energy and greenhouse emissions created by the on-site construction of alternative wooden, steel, and concrete assemblies. The main focus of the report is to determine the magnitude of the proportion that the construction process represents in the total energy usage (both direct and indirect energy) and green house emissions (Cole, 1998). The report ends recognizing a much larger amount of energy and greenhouse gas emissions under the assembling of concrete solutions on-site in comparison to both steel and timber. It further shows that the worker transportation to and from the construction site is the largest part of the energy usage for many structural assemblies being larger than the on-site equipment use and the equipment and materials transportation (Cole, 1998, see Figure 2.2).

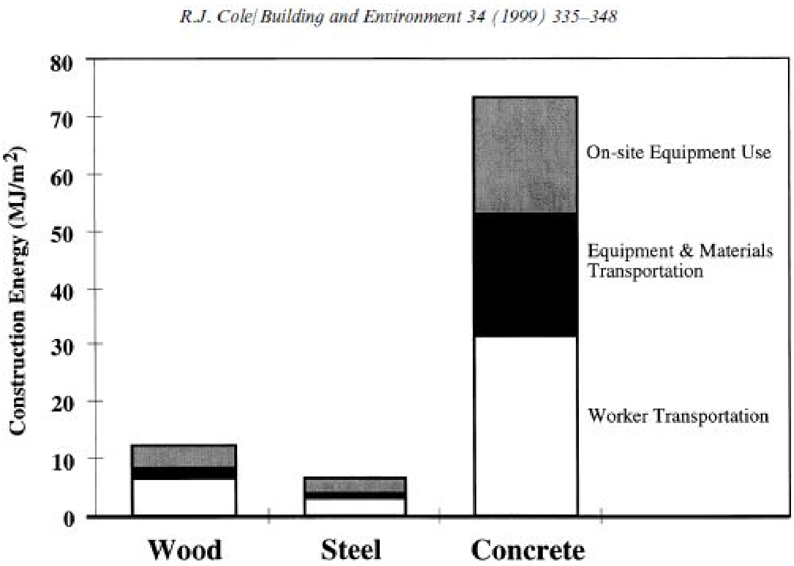

Figure 2.2: *Graph illustrating the average construction energy for three building materials and showing that the worker transportation has the largest energy contribution for all three*

The sub-project *Climate impact of construction processes. A report from IVA and the Swedish Construction Federation* is a part of the larger project *An Energy Efficient Society* which is a project created by the Royal Swedish Academy of Engineering Sciences, IVA, to promote more efficient energy use. The five sectors analysed in the project are buildings, industry, transport, forestry and agriculture while this sub-project only analyses the building sector and has as an aim to focus on the climate impact of construction processes in collaboration with the City of Stockholm and the Swedish Construction Federation. One of the important questions raised by the research is "Why are there not stricter requirements with respect to climate measures in construction projects". The authors claim that construction in Sweden is worth around 325 billion Swedish crowns each year which corresponds to 9 percent of the country's GDP and yet construction projects are being recognized as temporary while construction companies start new projects as soon as the previous is completed (Westlund et al., 2014). Other relevant observations like the limited knowledge about the climate impact of construction processes and the lack of insight and methods are also brought up and measures like needed dialogues, stimulations, follow-ups, and more efficient construction processes are recommended.

2.1 Conclusion of the literature review

The literature reviewed in this chapter affirms the importance of continuing investigating the critical impact that constructions have on the climate. It is highly relevant and includes a large number of discussions and conclusions that will be considered in the following parts of this report. There are likewise several aspects that need to be noted while using the conclusions from the literature above.

The articles were written between 1998 and 2020 and as technology on renewable energy, fuel types, fuel effectiveness, and production methods develop rapidly, it is important to recognize out-aged results that are not relevant anymore. For the same reasons, there is great uncertainties if the studies that are relevant today are applicable in the future. Some of the articles set an analysis period of 100 years when studying climate impact of buildings. This is not recommended by Boverket, 2020 as time frames larger than 50 years will most likely imply major renovation or reconstruction services on the buildings.

It is, in addition to the above, relevant to notice that the majority of the climate impact studies focus on the building materials separately rather than building components. The building components can be a combination of different materials, and different materials can also be included in several building components. Accordingly, to widen the knowledge about the climate impact from buildings, and to put the climate impact in context, it is necessary to analyse buildings using different comparison methods.

3

The Life Cycle Assessment

A Life Cycle Assessment (LCA) studies the environmental aspects and potential impacts of a product, a process, a service or an entire product system during its life cycle, from raw material acquisition through production, use and disposal. The method is defined by the international standards ISO 14040 and ISO 14044 where it is described how to produce an LCA and how to apply it to different products or services (Klöpffer and Grahl, 2014). This chapter describes the methodology behind an LCA and the different modules of a buildings life cycle that generally are included in this type of procedure.

3.1 LCA methodology

In this section the most common phases of an LCA are described in short, definition of goal and scope, life cycle inventory, life cycle impact assessment and interpretation of results according to ISO, 2006a and ISO, 2006b. It is often necessary to work iterative between these phases when conducting an LCA, which is illustrated in Figure 3.1 below.

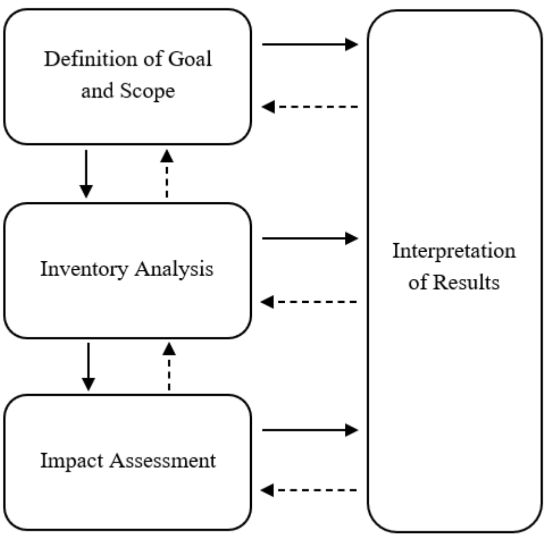

Figure 3.1: *The LCA procedure according to ISO, 2006a, where the dashed lines indicates possible repetitions in the iterative process.*

3.1.1 Definition of goal and scope

The first component of a standard LCA study should always be the definition of goal and scope according to Klöpffer and Grahl, 2014. Here, the concept and the goal of the study are specified and should clearly define what the objective of the study is and why an LCA is conducted. The context of the study should also be defined here, i.e for whom is the LCA to be conducted and in what way are the results to be presented. To decide the goal and scope for the LCA, different modeling specifications has to be made according to Baumann and Tillmann, 2004, such as technical system boundaries, impact categories, functional unit and the level of detail of the study. These modeling specifications are listed and described in short below.

- Technical system boundaries describe the processes that should be included. The selection of what to include is made in connection to the definition of goal and scope, and this affects the system boundaries of the flow chart that is produced in the inventory analysis.
- The selection of impact category includes the environmental impact type that the study will cover. Examples of impact categories are; use of resources, climate impact and acidification.
- The choice of relevant functional unit is made to be able to quantify the impact of the product system. Even if data acquisition does not need a functional unit initially, it is highly recommended to specify a functional unit as early as possible in an LCA procedure, according to Klöpffer and Grahl, 2014.
- Level of detail of the study describes the demands regarding data quality. Examples of different data types used in LCA are generic data that are general for common materials, often based on average values, and specific data for products which is data collected from an EPD or from the manufacturer of the product.

3.1.2 Life cycle inventory, LCI

The life cycle inventory analysis implies to establish a system model that corresponds to the demands from the definition of goal and scope (Baumann and Tillmann, 2004). The system model is often produced as a flow chart that shows the activities in the analysed system, such as production, transports, use stage, disposal, and the flow between these activities. When all the activities are stated, the data regarding these activities can be collected and quantified related to the chosen functional unit. The quantified environmental impact is added together for the entire system and can then be analysed in the life cycle impact assessment.

3.1.3 Life cycle impact assessment, LCIA

The quantified environmental impact from the LCI is described in the life cycle impact assessment phase. This is done through classification of the parameters from the LCI after the type of climate impact they contribute to. Then the relative contributions from the emissions and use of resource are calculated in each type of climate impact category. In this way the results from the LCI are converted to more relevant information, i.e information about environmental impact rather than information about resource use, as an example (Baumann and Tillmann, 2004). Another reason behind the LCIA is to collect information from the LCI into fewer parameters to make the results more understandable and easier to interpret in the next phase of the LCA.

3.1.4 Interpretation of results

The findings and results from the LCI and LCIA are interpreted in order to deliver results that corresponds to the defined goal and scope (ISO, 2006a). Conclusions based on this interpretation are drawn and recommendations should be provided to improve the analysed system.

3.2 Description of the modules included in a LCA procedure

The different stages of a building's assessment are divided into modules as stated in SIS, 2011. Each module, A-D, has sub-modules which are shown in Figure 3.2. The Modules A1 - C4 cover the effects and aspects that are directly connected to the production, operations and processes in the system boundary of the building. Module D, illustrated in Figure 3.3 provides on the other hand the net benefits of using materials and energy apart from the system boundary like secondary fuels, materials and exported energy (SIS, 2011).

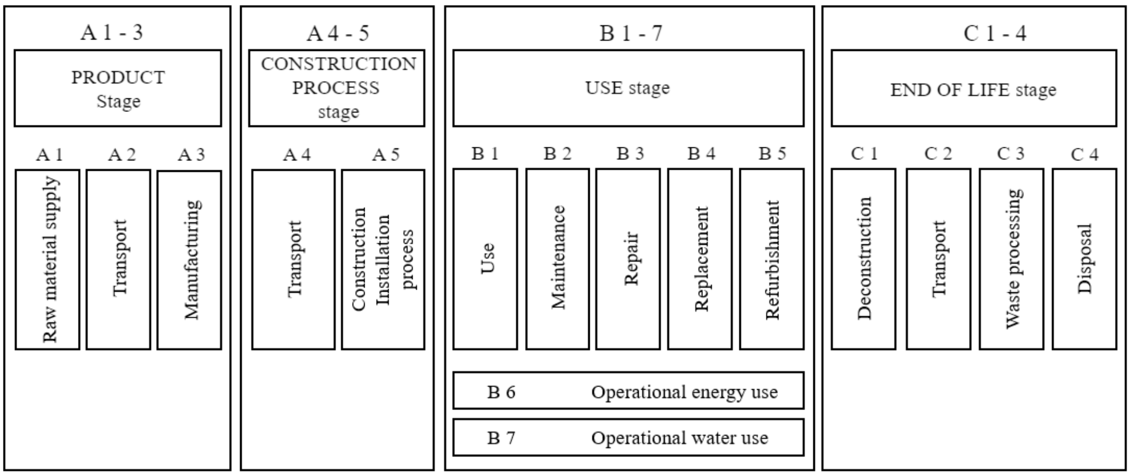

Figure 3.2: *Modules A-C of a standard LCA according to SIS, 2011, with information about a building life cycle.*

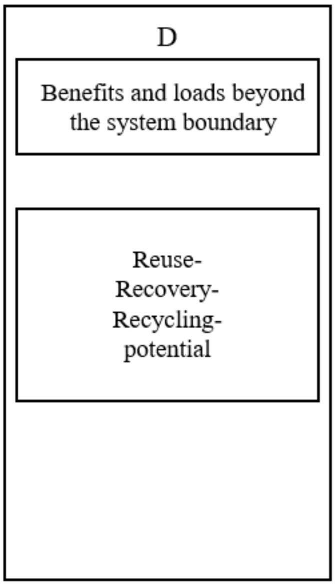

Figure 3.3: *Module D of a standard LCA according to SIS, 2011, with supplementary information beyond the building life cycle.*

3.2.1 Product stage: Module A1 - A3

The climate impact studied in the first module takes into account the production of the materials used in the construction of a building. The module is said to cover the "cradle to gate" of the materials (SIS, 2011). The aspects acknowledged in the product stage are:

A1. Raw material supply.
A2. Transport to manufacturing.
A3. Manufacturing.

3.2.2 Construction process stage: Module A4 - A5

The modules A4-A5 provide a picture of the climate impact that the construction process leads to. Module A4 analyses the impact coming from the transportation of materials from the factory gates to the construction site including any intermediate storage. This module also includes the transportation of equipment such as cranes and scaffolding.

Module A5 takes onto consideration the on-site aspects under the construction process:

A5.1. Waste and waste handling.
A5.2. The construction site's vehicles and machinery and their energy usage/fuel.
A5.3. Temporary works, including temporary works located off-site as necessary for the construction installation process.

A5.4. Provision of heating, cooling, ventilation, humidity control etc. during the construction process.
A5.5. Other climate impact from the construction process. Including over fertilization, blasting among others.

3.2.3 Usage stage: Module B1 - B7

Modules B1 to B7 generally cover the period of time that includes the time from the completion of the building to the demolition of the same.

The boundaries in this module contain the use of construction products that are utilized to protect and conserve the building in question, e.g. services like heating/-cooling, electricity for lighting, and water supplying. They also include maintenance aspects like cleaning and replacement of building parts (SIS, 2011).

Module B shall include the impacts that systems integrated in the particular building and building related furniture, fixtures and fittings have. Systems and other non building related furniture, fixtures and fittings should be excluded in this module.

B1. Boundary of the installed products in use.
B2. Boundary of maintenance.
B3. Boundary for repair.
B4. Boundary for replacement.
B5. Boundary for refurbishment.
B6. Boundary of the operational energy use.
B7. Boundary of the operational water use.

3.2.4 End of life stage: Module C1 - C4

The duration of the "End of life" cycle is set from the time that the building is decommissioned and is no longer expected for further use. The building's demolition contributes to a number of materials and other products that must be taken care of and either be recycled, reused or discarded. The scenarios where the different materials and products might end up should only be considered if these are proven to be economically and technically possible (SIS, 2011). The boundaries that are included in module C1 - C4 are the following.

C1. Boundary for the deconstruction.
C2. Boundary for transport.
C3. Boundary for waste processing for reuse, recovery or recycling.
C4. Boundary for the disposal.

3.2.5 Benefits and loads beyond the system boundary: Module D

The last module in the LCA recommended by IVL and standardized as European standard has the purpose to give information and support for future consequences from the future demolition. The environmental benefits or loads resulting from reuse, recycling and energy recovery are quantified in this module. This is a tool that acts as a guideline to take care of the forthcoming handling of residues the best way possible (Erlandsson et al., 2018). Module D is often not included in LCA:s since the results from this module are beyond the system boundary according to SIS, 2011.

An example of the outcomes of this module is the positive climate effect that timber residues and an effective energy extraction could have if the timber was used as fuel after demolition. The climate would then gain from the timber's usage instead of another material. Generally, the resulting suggestions from module D eventually become the same as the recommendations given by EU's waste hierarchy (Boverket, 2020), see Figure 3.4.

Figure 3.4: *The European Union's waste hierarchy illustrates an evaluation process showing the most favourable action to the least favourable (EuropeanCommission, 2021) .*

3.3 LCA softwares

There are a number of methods to create a building's LCA. The following methods are considered in this report because of their relevance and availability in the construction sector.

3.3.1 Simplified climate impact tools

Skanska's climate calculation team developed a simplified tool to calculate the climate impact of a building only using an excel template that contains a large number of materials and construction elements together with a respective emission factor. This tool is useful to make smaller analysis and get a picture of the climate impact that a building might have. The simplified climate impact tool only considers module A1 - A5.

3.3.2 ECO2

ECO2 is Skanska's climate calculation tool. It is a certified software that makes the most thorough and extensive climate studies that can be done at the moment. Skanska uses the software together with another internal software called SPIK in which material quantities are analysed for economical reasons. The more exact and detailed the SPIK file is from the beginning, the better the outcome from ECO2 becomes.

ECO2 is based on the software Anavitor which is a software that could be called "LCA for business benefits". Its purpose is to be used by parties that don't have a deep knowledge of LCA or LCC but still need or want the software's results for product development or to put requirements on their suppliers (Erlandsson, 2008). This process is explained in Figure 3.5 which is according to Anavitor, 2020 .

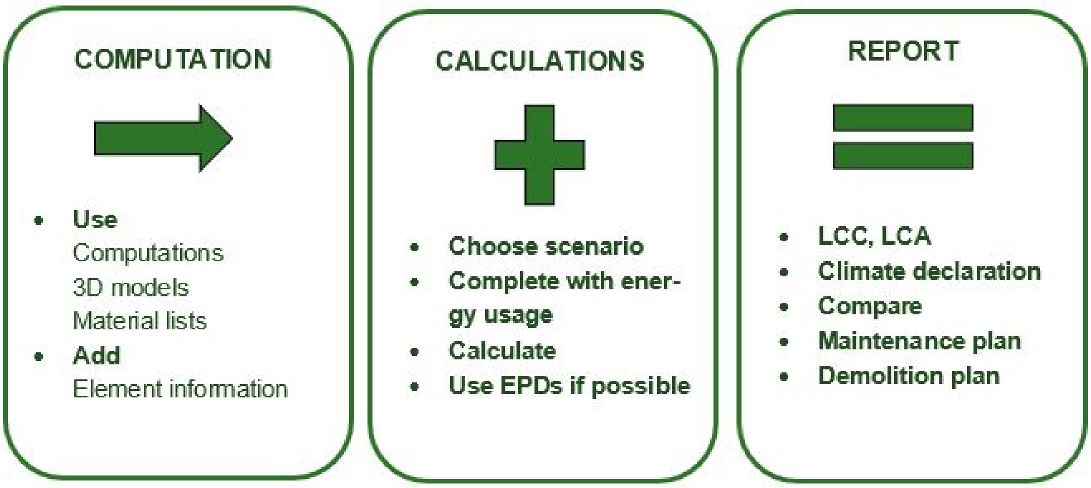

Figure 3.5: *Process from file to declaration according to Anavitor (Anavitor, 2020)*

3.3.3 BM

Byggsektorns Miljöberäkningsverktyg, called BM 1.0 in this thesis, is a software developed by IVL that was created because of the lack of an open climate impact tool that companies can use mutually and that results in unambiguous conclusions. The software is commonly used to generate climate declarations for all different kind of buildings (Erlandsson, 2018a).

The tool is designed to make a climate declaration as simple as possible but at the same time make enough thoroughly analyses so that comparisons between construction solutions are possible. BM 1.0 was developed with the cooperation of construction actors with a large influence on the requirements that are brought in procurement and design of buildings. As a result of this, BM 1.0 works as a guidance and support, to benefit the industry to achieve the national climate goals agreed (Erlandsson, 2018a).

BM analyses the LCA modules A1-A5 at the moment but IVL has the vision to continue the software's development so that a complete life cycle assessment can be created. Although IVL would like to evaluate a buildings climate impact and the buildings energy usage separately since the energy usage is strongly dependent on the assumptions made for future energy systems (Erlandsson, 2018a) .

3.4 LCA implementation in this report

This section presents the implementation of a life cycle assessment in this study. Information concerning how the LCA's modules will be managed and which software that are used for this particularly study will be given. The modules that will be considered in this report are presented in Figure 3.6 where these are marked with an x.

Firstly, only parts of the building that belong to the structural systems will be studied in the modules described previously. In addition to this, the roof structure and ground slab will be assumed to be the same for all structural systems due to simplifications and because of the small differences that they might have on the climate impact of each system.

The chosen analysis period for this study is set to 50 years, as Boverket, 2020 proposes as it is in line with how other countries in Europe approaches these types of analyzes. The analysis period is needed to calculate the emissions in the usage stage (module B) of an LCA. It is important to understand that this period is the time frame of the calculations and is not the same as the buildings service life.

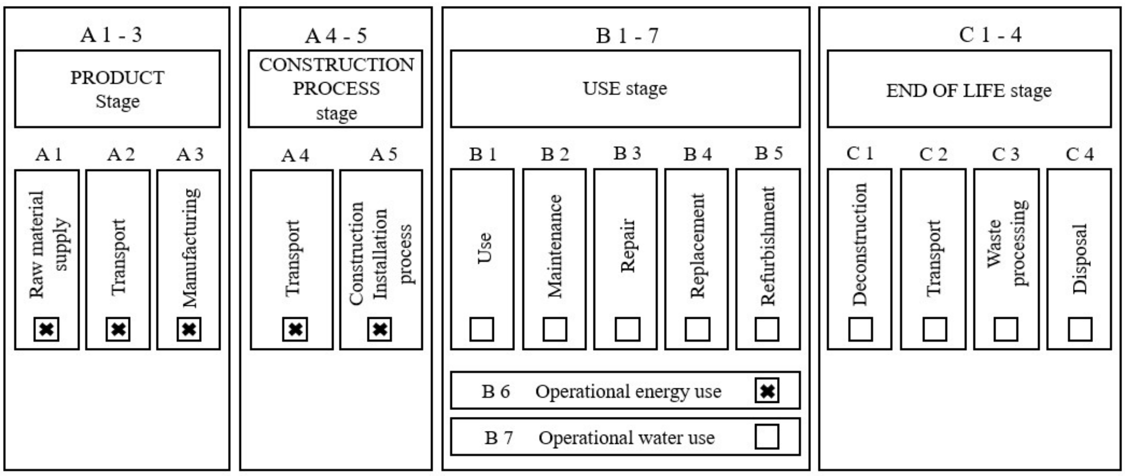

Figure 3.6: *Modules of a standard LCA that will be analyzed when the climate impact from four different structural systems is studied.*

3.4.1 Calculation of the impact in module A1-A3

The climate impact from module A1 - A3 is calculated by exporting quantity data from Revit drawings into the software BM 1.0. BM examines and recalculates the weight of the materials into climate impact by using generic global warming potential values for each element.

3.4.2 Material transportation, A4

The transportation of materials to the construction site, A4, and its climate impact is calculated with the same procedure as A1-A3. BM uses the weight of the materials and generic transportation data (such as transport distance and fuel type) to calculate the climate impact of each of the analysed elements in the building.

3.4.3 Waste and waste handling, A5.1

The waste and waste handling is approached using the generic values in BM for each materials. The values are material waste percentages that are multiplied to the total material weight given by Revit. The climate impact from the waste material is then calculated using the materials' GWP-value.

3.4.4 Impact from construction and installation, A5.2 -A5.5

The sub-modules A5.2-A5.5 are considered by using the calculated value of 10,35 $CO_2 - equivalents/m^2A_{temp}$ for all systems. The value, developed by climate experts at Skanska takes into account the whole reference building from the project *ABCD preschools*, including all non-bearing elements. The conservativeness in the value created by this will generate room for the differences between the systems regarding construction and installations.

There is otherwise a standard value developed by IVL, 2020, which is a conservative simplification of 30 $CO_2 - equivalents/m^2A_{temp}$. The value is developed to be applied for life cycle assessments where complete buildings are studied. For this reason the much larger standard value won't be used in this study.

3.4.5 Assumed energy usage of the building, B6

B6, the total energy usage under the period studied will be set to be the same for all the structural systems. This, on the grounds that the systems are assumed to have the same insulation properties and that the systems won't have any impact on the thermal climate of the building if they are changed between each other. The change could however impact the number and sizes of thermal bridges, but this will also be disregarded as their influence in the total energy usage is relatively small.

3.5 Environmental product declaration

An environmental product declaration, abbreviated EPD, is according to the international EPD system "an independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impact of product in a credible way" (System, 2020). A number of declarations will be used for the products utilised in the analysis of the preschool in this report. The GWP from these is compared to the generic GWP values in BM, which are values built on experiences from the construction sector (Erlandsson, 2021), in Table 3.1.

Table 3.1: *Improvement or deterioration of the global warming potential that a structural element has if data given by an EPD is used.*

EPD Material	**EPD GWP kg CO_2-e/kg**	**BM GWP kg CO_2-e/kg**	**Improvement Deterioration**
I-beams, Stena	1,02	1,71	40%
Concrete C40/50, Betongindustri	0,08	0,14	40%
HSQ beams, Bauforumstahl	1,13	1,71	34%
Reinforcement mesh, Celsa	0,41	0,58	29%
HD/F slabs, Strängbetong	0,14	0,18	26%
CLT, Martinsons	0,11	0,14	24%
Reinforcement bars, Celsa	0,41	0,52	21%
Green concrete C45/55, Skanska	0,12	0,14	17%
Filigree C40/50, Thomas Betong	0,19	0,18	-5%
Hollow steel columns, SSAB	2,41	1,71	-41%
LVL, Stora Enso	0,31	0,20	-50%
Planed timber, Stora Enso	0,09	0,06	-56%
Glulam beams, Moelven	0,18	0,09	-96%

3.5.1 The uncertainties of EPD:s

An EPD is certainly a complex study that can be calculated in different ways based on interpretations of standards, the ambitions set and the representatives involved. For this reason, it is crucial to understand and decide if an EPD can be used for a particular purpose. An approach to verify an EPD is using the LCA staircase, Figure 3.7, which illustrates the possibility to divide an LCA or EPD breaking them down into three steps. The first step is getting information related to the environmental performance of the product so that the magnitudes in the EPD can be compared to each other, the second is looking for and supporting environmental improvements, and then finally the third is comparing different data from various suppliers and solutions that have the same essential function that the function desired from the product in the EPD evaluated (Erlandsson, 2018b).

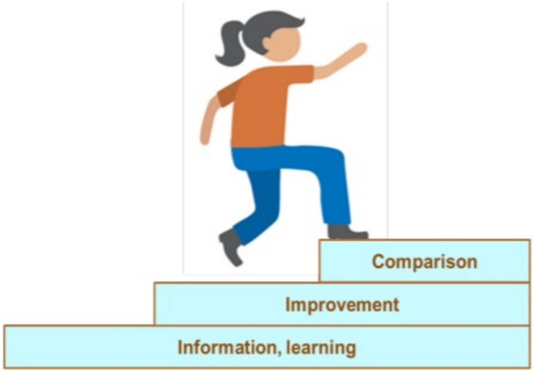

Figure 3.7: *The LCA stair is a method that simplifies an approach to investigate the quality of environmental data. The staircase leads to results that are used for comparisons, improvements or as an analysis to assess what is small or large.(Erlandsson, 2018b)*

4

Selection of Structural Systems

Several structural solutions are considered in this chapter. The chapter will describe the process of choosing the structural systems that will be selected to be analysed further in the report. This process entails considering a number of proposed systems which will be evaluated based on selected criteria parameters. The evaluation results will be used as guidance in the selection of the final systems to analyse. As stated in the method, the aim is to proceed with the most commonly used, and relevant structural systems to be used in the near future for this type of building.

4.1 Proposed systems

The systems that are proposed in this first stage of the evaluation are selected not only for their relevance in the construction sector but also for their material properties that later on might create suitable and clear comparisons between the systems' climate impact. These systems will be presented in a list below, together with short descriptions of the systems.

1. Reference system. Steel column and beam system with concrete hollow core slabs.
2. Steel column and beam system with filigree concrete slabs.
3. Steel column and beam system with prefabricated massive concrete slabs.

System 1 is the same system that is used in the reference concept built through Skanska's project *ABCD-preschools*. Skanska chose a system made of a steel columns and beams with prefabricated hollow core slabs. System 2 and 3 are inspired from this system and the only changes done are the type of slabs used.

4. Steel column and beam system with CLT slabs.
5. Steel column and beam system with prefabricated glulam modules.

Systems 4 and 5 are inspired by the reference system as well. But in these cases, the slabs are made of two timber solutions, cross laminated timber and glulam modules.

6. Precast sandwich outer walls with concrete hollow core slabs.
7. Glulam column and beam system with concrete hollow core slabs.

System 6 consists of hollow core concrete slabs supported by sandwich walls and steel columns together and beams. System 7 is similar as it also uses hollow core slabs but glulam columns and beams in this case.

8. Massive timber system made of CLT.
9. Glulam column and beam system with prefabricated glulam modules as floor slabs.
10. Cast-in situ concrete system.

The last three systems are one-material systems made of CLT, glulam and cast-in situ concrete. These systems are not used very often in real solutions but their purpose in this report is, as mentioned previously, to create clear comparisons between building materials.

4.2 A first evaluation of the systems

The first evaluation of the systems is carried out to select the structural systems that are most relevant to analyse in this study. The evaluation is based on three different criteria, with pertinent parameters that are described below. The evaluation will only be used as guidance in this selection. Thus, it is not necessarily the systems with the highest grades in the evaluation that will be analysed in this study. This, because too similar systems might end up with the highest grades, as well as the grading of the systems and parameters are subjective opinions.

4.2.1 Evaluation criteria

There are different parameters included in each criterion, which are mentioned and explained in Figure 4.1 as well as introduced in the following criteria explanation. The criteria and parameters are selected and also weighted against each other to achieve the most accurate outcome of the evaluation.

4.2.1.1 Economic aspects

The economic aspect is a recurrent aspect in almost every construction project and therefore it would be unwise to disregard it from the criteria used in this evaluation even if the aim of this study is not economically influenced. The two parameters that are being considered and will have an impact on the economical criterion of this evaluation are maintenance and building costs.

4.2.1.2 Structural design

The structural systems analysed need to be adapted for a preschool building. Accordingly, the systems should be able to partially or completely achieve a satisfactory level for a certain number of parameters that are important for that type of structure. These parameters in the evaluation are chosen to be complexity, flexibility and open areas.

4.2.1.3 Production

There is an abundance of productions methods that are possible to use depending on the type of material and the structural system that is chosen. Methods like, prefabrication and cast in-situ have pros and cons that are examined in the evaluation with the guidance of the two parameters "production time" and "risk of delays". These are chosen for the reason that time can be such a crucial moment in a project and might hold down costs and please the end user.

Criteria	Parameter	Explenation
Economic aspects	Maintenance	How regular is the maintenance of the system to make sure that it works effectively.
	Building cost	How expensive is the construction of the system.
Structural design	Complexity	How used to build this kind of structures is the construction industry.
	Flexibility	How easy is it to change the design of the building to evolve simultaneously with the need of the users.
	Open areas	How large are the open areas created by the system.
Production	Production time	How rapid is the production time.
	Risk of delays	How large is the risk for delays under the production time.

Figure 4.1: *Explanation of parameters handled in the evaluation of the systems.*

4.2.1.4 Weighting of the parameters included in each criterion

A weighting of the parameters mentioned above is performed with the purpose to make the future evaluation of the structural systems more accurate. Knowing that some of parameters might be more important than the others for the constructor of the structural system. The weighting of the parameters is done by ranking them between themselves as presented in Figure 4.2. If a parameter scores 1 it means that it is less important than the compared parameter, 2 means that it is equally important, and 3 means it is more important. This results in the parameters representing different proportions of the total value and thus being more or less important in the evaluation.

	Criterion parameter	1	2	3	4	5	6	7	Points	Percentage
1	Maintenance		1	1	1	1	1	1	6	7,14%
2	Building cost	3		3	2	2	3	3	16	19,05%
3	Complexity	3	1		1	1	2	3	11	13,10%
4	Flexibility	3	2	3		2	3	3	16	19,05%
5	Open Areas	3	2	3	2		3	3	16	19,05%
6	Production time	3	1	2	1	1		3	11	13,10%
7	Risk of delays	3	1	1	1	1	1		8	9,52%
									84	**100,00%**

Figure 4.2: *Weighting of the different criteria parameters against each other.*

4.3 Evaluation results

The structural systems proposed are evaluated according to the criteria previously mentioned. Each system is graded from 1-5 according to how well they perform against the parameters, where 1 is the worst grade (less favourable for the construction) and 5 is the best grade. To obtain the total grade for each system, their grades regarding all parameters are being multiplied to the corresponding weight factor of the parameter from Figure 4.2. This procedure and its results can be seen in Figure 4.3 below. It is important to be aware that the grading done in Figure 4.3 and also the weighting in Figure 4.2 of the parameters are completely developed and selected by own experiences and that they are not scientifically proven.

The four structural systems with the highest grades according to 4.3 are the systems 1, 2, 3, and 9. The systems are re-evaluated in next section to confirm that the selected systems are the most relevant for preschools constructors and for the future climate impact analysis.

Evaluation Criterion	Criterion Parameter	System number									
		1	2	3	4	5	6	7	8	9	10
Economic aspects	Maintenance	4	4	4	3	3	5	3	3	3	5
	Building cost	4	4	3	2	2	2	3	3	3	5
Structural design	Complexity	4	4	4	4	4	4	1	4	3	4
	Flexibility	5	4	3	4	3	2	4	3	4	1
	Open areas	5	4	4	3	3	5	4	3	3	2
Production	Production time	3	3	4	5	5	3	3	5	5	2
	Risk of delays	4	3	4	4	4	4	4	4	4	3
Total score		**4,25**	**3,77**	**3,62**	**3,49**	**3,3**	**3,37**	**3,21**	**3,49**	**3,55**	**2,95**

Figure 4.3: *Evaluation of the proposed structural systems.*

4.3.1 Re-evaluation and chosen structural systems

Here follows a short discussion about systems that scored high points but was not chosen to analyse in this study, and the final systems that were chosen. The final selection will be based on the score in the evaluation, how common the structural solution is at the moment and the potential of the system in the near future. System 3, steel column and beam system with prefabricated massive concrete slabs, scored high grades in for instance low complexity and fast production time. This system is although not commonly used in the construction sector because of its high material use and short spans compared to other prefabricated elements in the same material such as hollow core slabs and filigree.

The systems that will be analysed further in the continuation of the report are, for the above mentioned reasons, the following:

- System 1, the original system which was developed by Skanska continues to be relevant as it might be used for future preschools in Skanskas' *ABCD-preschools*. It also scored the highest points in our evaluation.

- System 2, as it is more common to use filigree slabs than massive concrete slabs, and because the combination of prefabricated and cast-in-situ leads to many structural benefits (Abetong, 2019).

- System 4 is a system where the use of a massive CLT solution is combined with a steel frame. Timber solutions aren't particularly standardized by the industry but their high carrying capacity and their potential of less negative climate impact is interesting to analyse and gives the system a large potential for future constructions (Brandt, 2015). This system is chosen as the replacement for system 3 which had the previously mentioned issues.

- System 9, which is a system entirely made of glulam, is chosen to be analyzed as timber constructions are becoming more and more interesting and coveted by clients. This is proven by the Swedish glulam industry sales and production, which have increased steadily over the past years, according to SvensktTrä, 2020. The future potential of a solution like this is big but the system is not commonly used at this time. It is therefore important to explore the potential reduction of climate impact from this system compared to more established structural systems.

For the above mentioned reasons the four final structural systems that will be preliminary dimensioned and analysed further are the systems shown in Table 4.1.

Table 4.1: *Four final structural systems to analyse regarding climate impact.*

Final system number	Short description of the structural system
1	Steel column and beam system with concrete hollow core slabs
2	Steel column and beam system with filigree concrete slabs
3	Steel column and beam system with massive CLT floor slabs
4	Glulam column and beam system with prefabricated glulam module floor slabs

5

Description of the Chosen Structural Systems

An existing preschool project was used as a reference building in this report, where the preschool is a two storey building with room for up to nine departments and 108 children. It has a total BTA of 1337 m^2, but this area could change between the different systems due to differences in the structural system. Instead, the same A_{temp} was used in all systems, which is 1242 m^2 for the reference preschool. The same ground slab will be used in all systems, which is a concrete slab made of C45/55 with thickness 120 mm. The same applies for the roof structure which is a truss system of planed timber beams and glulam beams. Figure 5.1 and Figure 5.2 illustrate the future floor plan for each storey of the reference building

Figure 5.1: *Illustration of the floor plan of the first floor in the reference building.*

Figure 5.2: *Illustration of the floor plan of the second floor in the reference building.*

The four different structural systems that have been analysed are described in the following sub chapters. It is important to have in mind that one of the most crucial aspects for the *1000 preschools* project is that the structural systems are flexible since the needs in the building might change in the future. That is why no structural system in this report will have any bearing inner walls.

5.1 System 1: Steel column and beam system with concrete hollow core slabs

This system is the reference system that will be used for preschools in Skanska's project *ABCD-preschools*. The structural system is based on hollow steel columns that are integrated in both the outer and inner walls. The floor consists of 200 mm prefabricated hollow core slabs and a layer of 60 mm cast-in-situ concrete on top, and are supported by HSQ steel beams. A section of a connection between the outer walls and floor slabs can be seen in Figure 5.3.

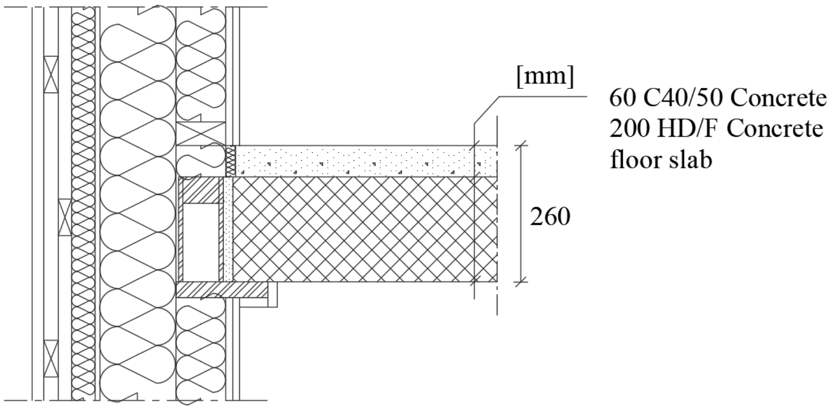

Figure 5.3: *Section of the connection between outer walls and floor slabs in system 1.*

5.2 System 2: Steel column and beam system with filigree concrete slabs

This system is similar to system 1, with the difference that the concrete slabs are made of prefabricated filigree concrete slabs with a cast-in-situ layer on top where installations can be placed. This solution is appreciated as it is a combination of two construction methods with the advantages that prefabrication brings to the table and the flexibility of cast-in-situ. On the other hand, it requires more project planning than a complete cast in situ project and might for this reason lose its time advantages if many additions have to be implemented (Olofsson & Sollie, 2011).

The reinforcement in this system is casted into the filigree concrete slab already in the factory and a homogeneous concrete slab is created when the top layer of concrete is casted on (SvenskBetong, n.d.). An illustration of a filigree concrete slab is shown in Figure 5.4.

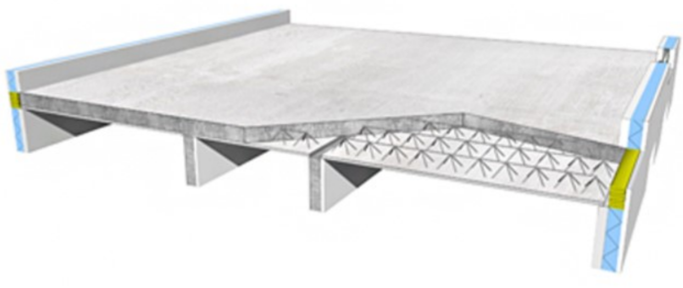

Figure 5.4: *Example of a reinforced filigree slab with a thick cast-in-situ layer on top creating a homogeneous concrete slab (Byggelement, 2016).*

The reinforced filigree slab studied is designed to be 50 mm thick and have a 250 mm thick cast-in-situ layer on top. The bearing columns and beams of the system are made with the same materials as the ones in system 1. A section of the connection between the outer walls and the floor slabs is shown in Figure 5.5 below.

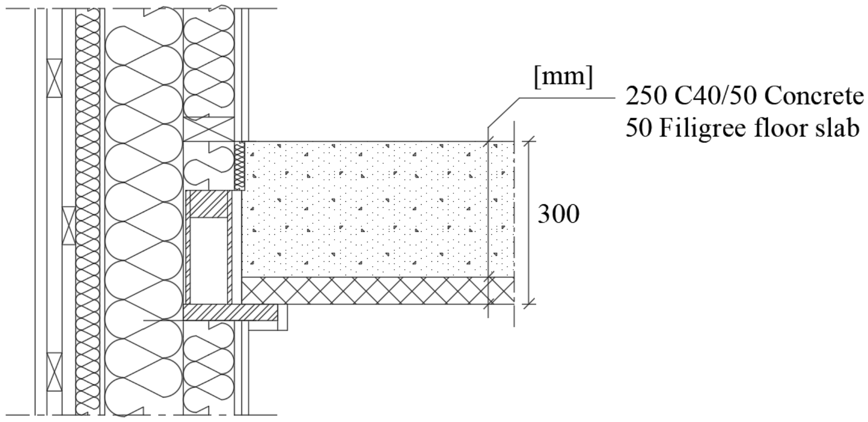

Figure 5.5: *Section of the connection between outer walls and floor slabs in system 1.*

5.3 System 3: Steel column and beam system with CLT slabs

Steel columns and HSQ beams will act as supports for timber slabs made of 230 mm cross laminated timber in system 3. The CLT slab is supplemented with the Granab floor system to achieve the sound requirements of sound class C for all new healthcare facilities and preschools in Sweden, according to Boverket, 2017. The Granab floor system consists of 200 mm galvanized steel studs with insulation between the studs, a 22 mm chipboard on top and pertinent gypsum boards and fire boards (Granab, 2019). A section of a connection between outer walls and floor slabs is illustrated in Figure 5.6 below.

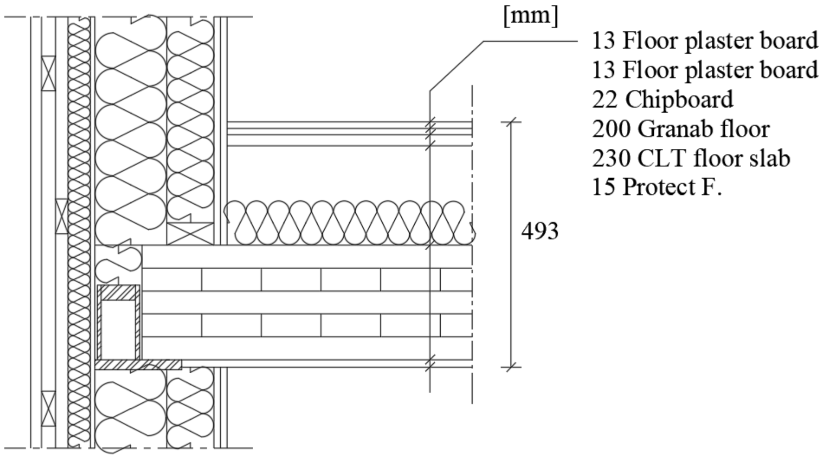

Figure 5.6: *Section of a connection between the outer walls and the floor slab, based on a solution from Granab AB.*

To get an understanding of how this could look like, an example solution is shown in Figure 5.7 below. The difference between this example solution and the one that is used in this study is the height of the steel studs and that the parquet flooring is not included in this study.

Figure 5.7: *Illustration of an example solution of Granab floor installed on top of a CLT slab (Granab, 2019).*

5.4 System 4: Glulam column and beam system with prefabricated glulam modules

System 4 is a system that will act as a reference for timber structural systems. Glulam columns and beams are supporting the floor slabs which are modules made of a glulam frame with an LVL board on top. The floor modules, called *Trä8*, are produced in Moelven's factory and are then ready to be installed at the construction site. The floor need to be supplemented with a concrete screed when the slabs are installed to ensure that they correspond to the acoustic requirements. A section of a connection between the outer walls and Moelven's floor slab is illustrated in Figure 5.8.

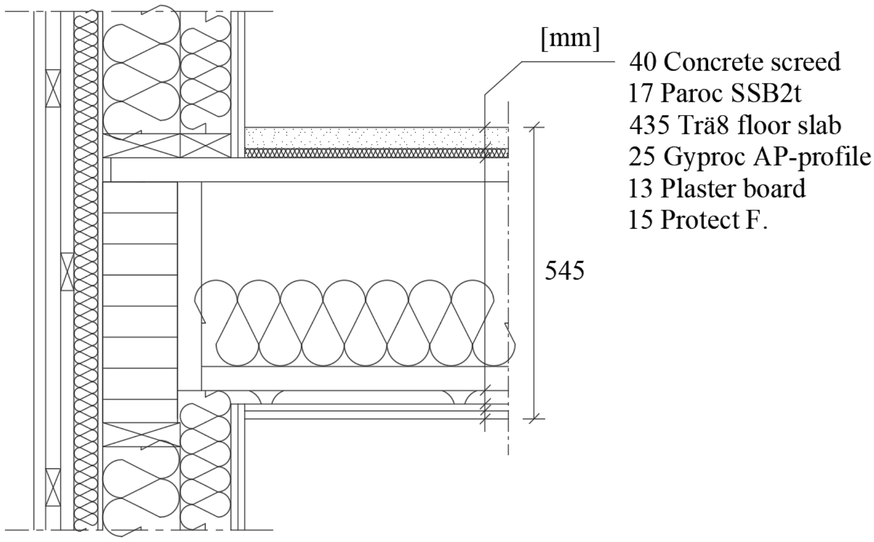

Figure 5.8: *Section of a connection between the outer walls and the floor slab, based on a floor slab solution from Moelven.*

The modules are designed as a stud system with glulam beams and a LVL top plate with mineral wool insulation between the studs, see Figure 5.9, where the modules without the concrete layer are illustrated by Moelven, 2021.

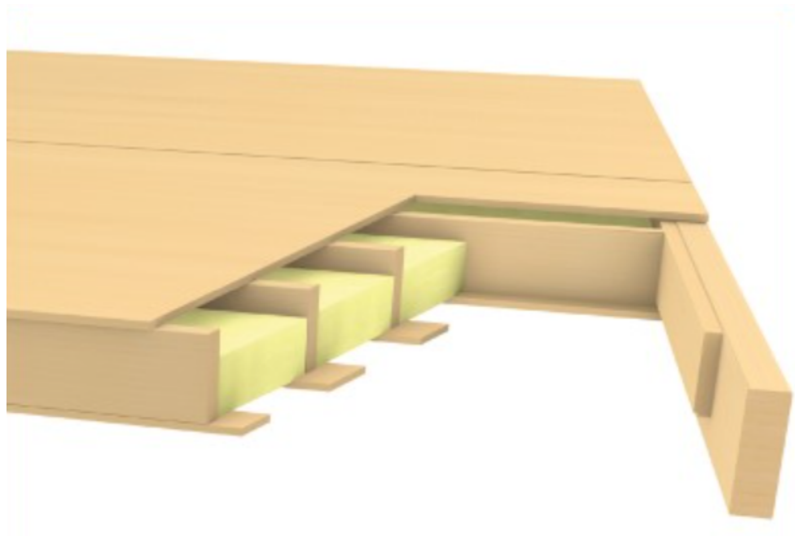

Figure 5.9: *Prefabricated hollow core glulam modules illustrated by Moelven Industrier ASA (Moelven, 2021).*

6

Preliminary Sizing

As the most relevant structural systems for this study have been selected, some structural members need to be analysed and dimensioned. This is in order to verify that the structural systems are feasible and that the different components have sufficient capacity for the loads to which they are subjected. The relevant capacities that are looked into are shear- and moment capacity. The interaction between axially compression and bending is also checked to make sure that the structural systems can handle the wind load and compression forces simultaneously.

The reference structural system (system 1) will not be analysed, since it is already designed by Skanska, nor the concrete slab on the ground floor or the roof structure for any of the selected systems. The floor slabs in system 2, system 3, and system 4 do not need to be analysed either since they are solutions that have been preliminary sized by from SvenskBetong, n.d., Martinsons, n.d., and Moelven, 2021 respectively. Moelven's (Asplund, 2021) and Martinson's solutions were created with a fixed cross section dependent on maximum span lengths. The calculations for timber members and steel members will be performed according to Eurocodes described in SIS, 2004 and SIS, 2005 respectively, and can be seen in Appendix A.1, A.2 and A.3. The structural members that have been analysed are shown in Table 6.1 below:

Table 6.1: *Elements that will be preliminary sized in the different structural systems.*

System Number	Steel Columns	Steel Beams	Glulam Columns	Glulam Beams
2	x	x		
3	x	x		
4			x	x

6.1 Loads and load combinations

The loads acting on the structural members are the variable loads from wind, snow and the imposed loads on the floor slabs, and the permanent dead weights. These loads will be combined according to the requirements mentioned above.

Table 6.2: *Loads acting on the structural members.*

Parameter	Denomination	
Dead weights	$G_{k,j}$	$j \geq 1$
Main variable load	$Q_{k,1}$	
Variable loads	$Q_{k,i}$	$i > 1$

Where $G_{k,j}$ is the sum of all the dead weights acting on the structural member, and $Q_{k,i}$ is the sum of all variable loads, excluding the main load, acting on the structural member. The partial safety factors can be seen in Table 6.3 and the reduction coefficients for non-main variable loads can be seen in Table 6.4.

Table 6.3: *Partial safety factors used for load combinations.*

Loading type		ULS	SLS
Permanent, γ_g	Unfavourable	1.35	1.0
	Favourable	1.0	1.0
Variable, γ_q	Unfavourable	1.5	1.0
	Favourable	0	0

The ULS safety factors will be used for checks regarding shear force and moment capacities etc., while the SLS safety factors are applied when calculating the deflection of the slabs and beams.

Table 6.4: *Reduction coefficients for the variable loads that affect the preschool building.*

Action	Ψ_0	Ψ_1	Ψ_2
Imposed load, category C	0.7	0.7	0.6
Wind load	0.3	0.2	0
Snow load	0.8	0.6	0.2

The reduction factors used in the load combination depends on which load category that is relevant for the building. For a preschool, the relevant category for the imposed load is C1 (areas with tables such as schools, cafés, restaurants, etc). This entails that the imposed load, q_k, acting on the floor slabs is $3.0kN/m^2$. The imposed load in ULS may also be reduced for category C by applying a reduction factor α_A which is calculated by equation 6.1.

$$\alpha_A = \frac{5}{7} \cdot \Psi_0 + \frac{A_0}{A} \leq 1.0 \qquad (6.1)$$

Where Ψ_0 is the reduction coefficient for category C, A_0 is the reference area of

$10m^2$, and A is the loaded area that affects the analysed structural member.

Regarding the snow load, a rather conservative value of $3.0kN/m^2$ is chosen for the characteristic snow load s_k. This to ensure that the solutions are feasible in most parts of Sweden, see Appendix B.1. Because of this snow load, its reduction coefficient, Ψ_0, is set to 0.8. Combining these parameters, factors and coefficients, the final equation used for the calculations of preliminary sizing of structural members in ULS is shown in equation 6.2 below:

$$q_d = \gamma_g \cdot G_{k,j} + \gamma_{q,1} \cdot Q_{k,1} + \gamma_{q,i} \cdot \Psi_{0,i} \cdot Q_{k,i} \tag{6.2}$$

The ULS load combination above is divided into different cases where each different variable load might act as main load. The loads that are not main loads are multiplied with a reduction factor. This is done in order to obtain the worst load scenario for each structural member that is analysed.

The deflection calculations of the slabs are done with characteristic load combinations, SLS. This type of combination is shown in equation 6.3:

$$q_d = G_{k,j} + Q_{k,1} + \Psi_{0,i} \cdot Q_{k,i} \tag{6.3}$$

To calculate the deflection of the beams the quasi-permanent load case is used which is as equation 6.4 below:

$$q_d = G_{k,j} + \Psi_{2,i} \cdot Q_{k,i} \tag{6.4}$$

The timber beams also need an additional deflection check with the frequent load combination in SLS, shown in equation 6.5 below:

$$q_d = G_{k,j} + \Psi_{1,1} \cdot Q_{k,1} + \Psi_{2,i} \cdot Q_{k,i} \tag{6.5}$$

6.2 Resulting dimensions

The resulting dimensions of the preliminary sizing for each analysed structural member will be presented in this chapter. All calculations are presented in Appendix A.1, A.2 and A.3.
To calculate the maximum moment and shear force acting in the beams elementary cases from Appendix B.1 have been used. Elementary cases have also been used for the deflection calculations of the beams. A continuous beam over three spans have been analysed to calculate the deflection of the steel beams in system 2 and system 3. For the glulam beams in system 4 a continuous beam over two spans have been analysed. The span length for the beams is set to 6 m in the building, which applies to the beams in all systems.

All columns have been checked regarding axial force, but the columns in the outer walls need additional checks to ensure that they are feasible by considering the wind load on the side of the building. These checks are done for the moment capacity and interaction between moment and axial force. Columns on the first floor are subjected to the maximum axial force when the imposed load act as main load, while columns on the second floor are subjected to the maximum axial force when the snow load act as main load. The maximum moment and interaction in columns in the outer walls on both floors are obtained when wind load act as main load.

In the coming sections, the preliminary dimensions for all considered elements for all systems will be presented. To provide an overview of the structural system and its structural parts, an example 3D-view with highlighted elements can be seen in Figure 6.1. Note that Figure 6.1 shows a 3D-view of system 4 that mainly consists of glulam members, and that structural members in other systems may look different.

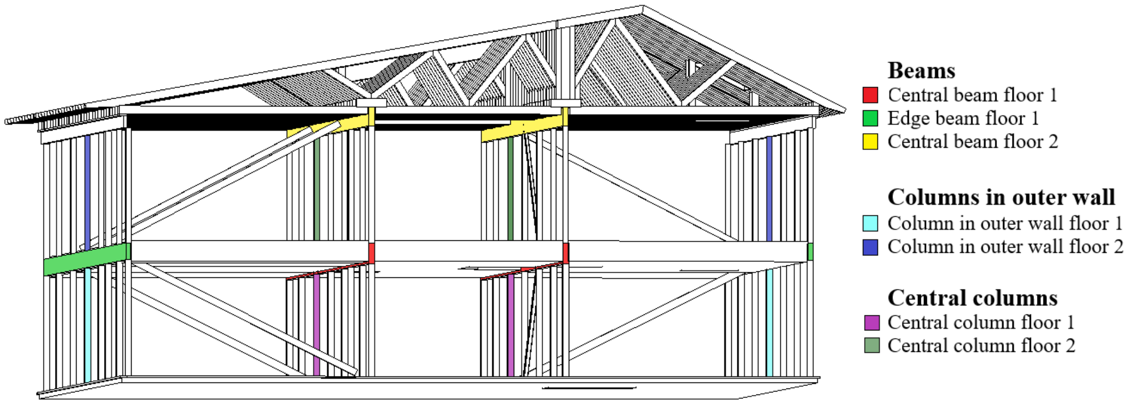

Figure 6.1: *Illustration of the structural system with the preliminary sized members highlighted.*

6.2.1 System 2

The filigree concrete slabs used in this system are heavier than the hollow core slabs used in the reference building which means the beams and columns have to be re-dimensioned and checked in order to see if they have enough capacity.

6.2.1.1 Steel beams

The calculations for the beams in this chapter are according to Eurocodes together with torsional moment capacities calculated according to Persson, 2015. A HSQ beam and a one sided HSQ beam with the abbreviations used in the result tables are shown in Figure 6.2.

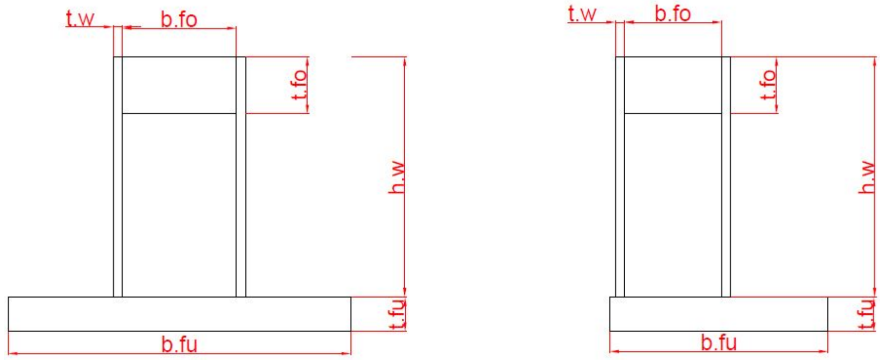

Figure 6.2: *HSQ beams and abbreviations of their dimensions*

The resulting dimensions of the HSQ beams used in system 2 can be seen in Table 6.5 below. The only difference towards the reference system is that the height of the web needed to increase slightly to handle the increased weight from the filigree slabs.

Table 6.5: *Results from the preliminary sizing of steel beams in system 2.*

Beam type	**Dimensions [mm]**					
Central beam	t_w	h_w	b_{fo}	t_{fo}	b_{fu}	t_{fu}
HSQ beam S235	8	220	100	50	300	30
Edge beam	t_w	h_w	b_{fo}	t_{fo}	b_{fu}	t_{fu}
HSQ beam S235	8	210	85	50	175	30

With these dimensions the bending moment and shear force in Table 6.6 were obtained. The table also show the capacities and the utilization rate regarding bending moment and shear force acting in the beams.

Table 6.6: *Capacity check and utilization ratio for the HSQ steel beams in system 2, regarding bending moment and shear force.*

Beam type		**Bending moment [kNm]**	**Shear force [kN]**
Central beam	Design load	219.30	257.69
	Capacity	368.19	477.58
	Utilization	60 %	54 %
Edge beam	Design load	126.51	147.77
	Capacity	228.61	455.88
	Utilization	55 %	32 %

The HSQ beams have a low slenderness which means that they do not need to be checked regarding shear buckling. This is shown in the calculations in Appendix A.1. However, the one sided edge beams are not loaded symmetrically i.e. the load from the slabs is only applied to one side of the beam. This means they have to be checked regarding torsional moment and the results from this check can be seen in Table 6.7 below.

Table 6.7: *Capacity check and utilization ratio for for the edge beams in system 2 regarding torsional moment.*

Beam type		**Torsional moment [kNm]**
Edge beam	Design load	8.62
	Capacity	34.60
	Utilization	25 %

The deflections of the HSQ beams are presented in Table 6.8. The table also shows the recommended limit of L/300 so that the results can be compared to common construction recommendations.

Table 6.8: *Resulting deflections of the beams in system 2, with the Quasi-permanent load case.*

Beam type	**Deflection limit L/300 [mm]**	**Deflection [mm]**
Central beam	20	19.13
Edge beam	20	16.97

6.2.1.2 Steel columns

The resulting dimensions, axial force, capacity and utilization ratios for the steel columns in the middle of the building are shown in Table 6.9. These columns are only subjected by an axial force unlike the outer columns that are additionally subjected to a horizontal load, as mentioned before. The latter and their results are presented in Table 6.10.

Table 6.9: *Results from the preliminary dimensioning of steel columns in the center of the building in system 2.*

Column type and dimensions		Axial force [kN]
Floor 1	Design load	547.09
VKR S235	Capacity	645.24
$150 \cdot 100 \cdot 8[mm]$	Utilization	85 %
Floor 2	Design load	139.89
VKR S235	Capacity	259.65
$80 \cdot 80 \cdot 7.1[mm]$	Utilization	54 %

Table 6.10: *Results from the preliminary dimensioning of steel columns in the outer walls of the building in system 2.*

Column type and dimensions		Bending moment [kNm]	Axial force [kN]	Interaction
Floor 1	Design load	5.40	314.11	0.76
VKR S275	Capacity	16.46	703.57	1.0
$150 \cdot 100 \cdot 8$	Utilization	33 %	45 %	76 %
Floor 2	Design load	5.40	77.66	0.99
VKR S275	Capacity	7.33	270.40	1.0
$80 \cdot 80 \cdot 7.1$	Utilization	74 %	29 %	99 %

6.2.2 System 3

The massive CLT floor slabs have a lower weight than the hollow core slabs in the reference building, which makes an optimization possible to use smaller beams and columns in this system.

6.2.2.1 Steel beams

All steel beams checked for this solution and the results shown are for HSQ beams and the one-sided HSQ beams. Their dimensions with the belonging abbreviations can be seen in Table 6.11.

Table 6.11: *Results from the preliminary sizing of steel beams in system 3.*

Beam type	**Dimensions [mm]**					
Central beam	t_w	h_w	b_{fo}	t_{fo}	b_{fu}	t_{fu}
HSQ beam S235	8	160	100	30	300	20
Edge beam	t_w	h_w	b_{fo}	t_{fo}	b_{fu}	t_{fu}
HSQ beam S235	8	150	69	30	175	20

With these dimensions, the maximum bending moment and shear force shown in Table 6.12 were obtained. The utilization of the beams are also shown in the same table and represent the magnitude of the design load in relation to the capacity. Shear buckling effects didn't need to be considered as the beams showed low slenderness.

Table 6.12: *Results from the preliminary dimensioning of steel beams in system 3.*

Beam type		**Bending moment [kNm]**	**Shear force [kN]**
Central beam	Design load	92.30	61.94
	Capacity	174.76	325.63
	Utilization	53 %	19 %
Edge beam	Design load	56.93	62.28
	Capacity	107.05	325.63
	Utilization	53 %	19 %

The check regarding torsional moment in the one sided HSQ edge beams can be seen in Table 6.13 below.

Table 6.13: *Capacity check and utilization ratio for for the edge beams in system 3 regarding torsional moment.*

Beam type		**Torsional moment [kNm]**
Edge beam	Design load	3.51
	Capacity	25.41
	Utilization	14 %

The deflections of the HSQ beams using the quasi-permanent load case are presented in Table 6.14. The table also shows the recommended limit of L/300 to compare the results with common construction recommendations.

Table 6.14:

Resulting deflections of the beams in system 3, with the Quasi-permanent load case.

Beam type	Deflection limit L/300 [mm]	Deflection [mm]
Central beam	20	19.61
Edge beam	20	18.13

6.2.2.2 Steel columns

The resulting dimensions, axial force, capacity and utilization ratios for the steel columns in the middle of the building are shown in 6.15. These columns are only subjected by an axial force unlike the outer columns that are additionally subjected to a horizontal load, as mentioned before. The latter and their results are presented in Table 6.16.

Table 6.15: *Results from the preliminary dimensioning of steel columns in the center of the building in system 3.*

Column type and dimensions		Axial force [kN]
Floor 1	Design load	276.63
VKR S235	Capacity	321.40
$120 \cdot 80 \cdot 6.3[mm]$	Utilization	86 %
Floor 2	Design load	139.89
VKR S235	Capacity	236.25
$80 \cdot 80 \cdot 6.3[mm]$	Utilization	59 %

Table 6.16: *Results from the preliminary dimensioning of steel columns in the outer walls of the building in system 3.*

Column type and dimensions		Bending moment [kNm]	Axial force [kN]	Interaction
Floor 1	Design load	5.40	157.99	0.79
VKR S235	Capacity	13.30	395.80	1.0
$100 \cdot 100 \cdot 6.3$	Utilization	41 %	41 %	79 %
Floor 2	Design load	5.40	77.66	0.99
VKR S235	Capacity	9.56	315.47	1.0
$90 \cdot 90 \cdot 6.3$	Utilization	56 %	25 %	79 %

6.2.2.3 CLT slabs

The slab chosen for this system has been previously dimensioned by Martinsons. Table 6.17 shows the deflection result that has been published by the company for a slab up to 6,8 m long subjected to the imposed load that might appear in a school building ($3.0kN/m^2$). This load case excludes the load from inner walls, installations and the parts of the slabs that aren't made of CLT. The deflection will not surpass the deflection limit for a load up to $5.0kN/m^2$, which is higher than the load case with everything included would result in (Martinsons, n.d.).

Table 6.17: *Results from the preliminary dimensioning of CLT slabs in system 3 according to Martinsons.*

Span length and thickness	**Deflection limit L/300**	**Deflection L/423**
$L = 6.45[m]$ $t = 230[mm]$	$21.5[mm]$	$15.4[mm]$

6.2.3 System 4

This system have most differences compared to the reference system, which means that there are more structural members in this system that needs to be dimensioned. In addition to the columns and beams in the previous systems that have been dimensioned, the central beams between floor 2 and the roof needs to be dimensioned as well.

6.2.3.1 Glulam beams

Design loads, capacities and utilization ratios regarding bending moment and shear force for each type of glulam beam in this system are shown in Table 6.18. The table contains the dimensions and timber quality in addition to the sectional forces.

Table 6.18: *Results from the preliminary dimensioning of glulam beams in system 4.*

Beam type and dimensions		**Bending moment [kNm]**	**Shear force [kN]**
Central beam between floor 1 and 2	Design load	136.39	113.66
GL30c	Capacity	155.60	114.05
$540 \cdot 165[mm]$	Utilization	88%	99%
Edge beam between floor 1 and 2	Design load	83.57	69.64
GL30c	Capacity	93.37	94.08
$450 \cdot 140[mm]$	Utilization	90%	74%
Central beam between floor 2 and the roof	Design load	103.20	79.16
GL30c	Capacity	111.90	88.70
$495 \cdot 140[mm]$	Utilization	92%	89%

The resulting deflections of the glulam beams are stated in Table 6.19, with associated deflection limits. The glulam beams have been checked with both frequent and quasi permanent load case.

Table 6.19: *Resulting deflections of the glulam beams in system 4, with the Frequent and Quasi-permanent load case.*

Beam type	**Load case**	**Deflection limit, [mm]**	**Deflection [mm]**
Central beam between floor 1 and 2	Frequent	L/375, 16	7.16
	Quasi-permanent	L/300, 20	15.93
Edge beam between floor 1 and 2	Frequent	L/375, 16	8.78
	Quasi-permanent	L/300, 20	18.08
Central beam between floor 2 and the roof	Frequent	L/375, 16	5.86
	Quasi-permanent	L/300, 20	3.89

The dimensions of the columns in the middle of the building and the axial force, capacity and utilization ratio are shown in Table 6.20.

6.2.3.2 Glulam columns

Table 6.20: *Results from the preliminary dimensioning of glulam columns in the center of the building in system 4.*

Column type and dimensions		Axial force [kN]
Floor 1	Design load	296.18
GL30c	Capacity	315.14
$160 \cdot 160[mm]$	Utilization	94 %
Floor 2	Design load	139.89
GL30c	Capacity	199.51
$140 \cdot 140[mm]$	Utilization	70 %

The dimensions of the columns in the oter walls of the building and the acting loads, capacities and utilization ratios are shown in Table 6.21.

Table 6.21: *Results from the preliminary dimensioning of glulam columns in outer walls of the building system 4.*

Column type and dimensions		Bending moment [kNm]	Axial force [kN]	Interaction
Floor 1	Design load	4.70	174.60	0.93
GL30c	Capacity	13.25	307.42	1.0
$160 \cdot 160[mm]$	Utilization	35 %	57 %	93 %
Floor 2	Design load	4.50	77.66	0.87
GL30c	Capacity	8.87	204.27	1.0
$140 \cdot 140[mm]$	Utilization	51 %	38 %	87 %

7

Results

The results presented in this chapter are relevant for preschool buildings with a life period of 50 years. The results do not take into consideration the climate impact that the piling might have and nor parts of the building that are not included in the structural systems. The energy usage for each system is equally large for all systems, and has been calculated by Skanska's energy calculation experts.

For each structural system, two different cases have been studied. One case with climate impact acquired from generic values from BM, and one case with climate impact acquired from product specific EPD:s. The latter case includes EPD:s for some elements that are used in the reference building, and some EPD:s for more climate smart alternatives, like green concrete. Three result graphs are shown for each of the four concepts:

1. GWP in form of kg $CO_2 - equivalents/m^2 A_{temp}$ for the modules of the building's life cycle assessment under the studied time of 50 years.

2. Distribution of GWP for the different materials and components from the product stage (module A1-3):

    (a) Using generic values from BM.

    (b) Using values from product specific EPD:s.

A short analysis of the climate impact that a concrete casting would have instead of the granab-solution used for the CLT slab in system 3 was performed in addition to the above mentioned analysis. This will make it possible to compare the more modern solution that Granab has developed to the more traditional cast-in-situ solution.

The reference building has previously been analysed by sustainability specialists and climate experts at Skanska. Their results showed that the building had a climate impact (modules A1-A5) of 261 kg CO_2-equivalents/m$^2 A_{temp}$. This will later on be compared to the results obtained in this study where only the structural system is analyzed.

7.1 System 1: Steel column and beam system with concrete hollow core slabs

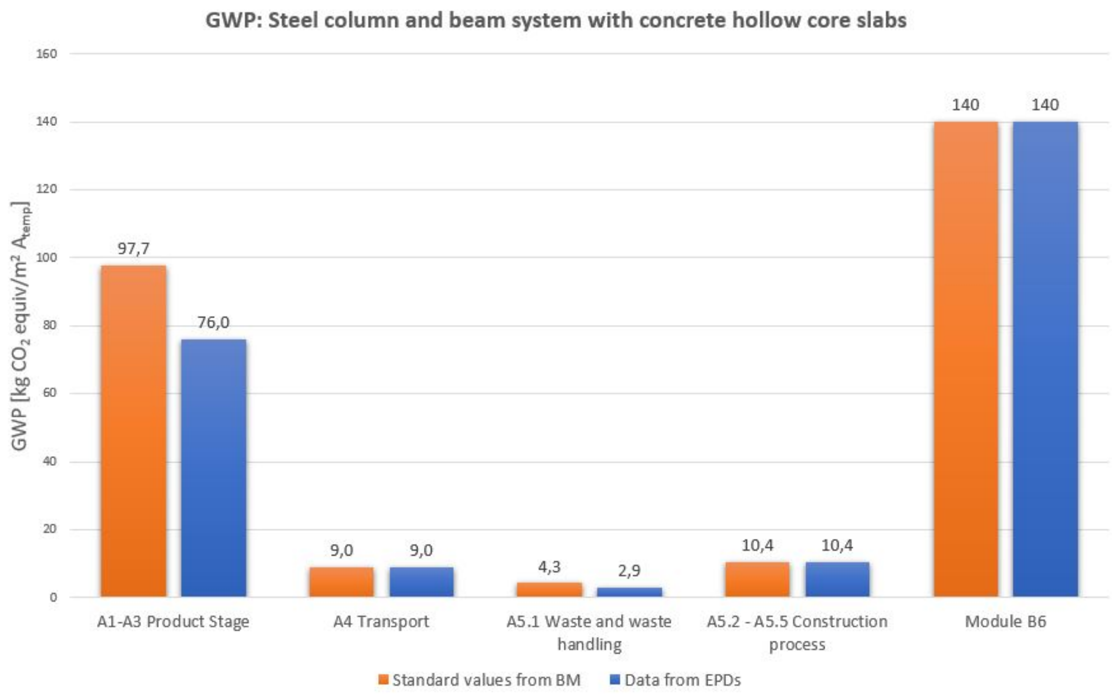

Figure 7.1: *GWP as result of generic values from BM (orange) and data from material specific EPD:s (blue). The potential is divided into modules where B6, operational energy use, is identical for both cases.*

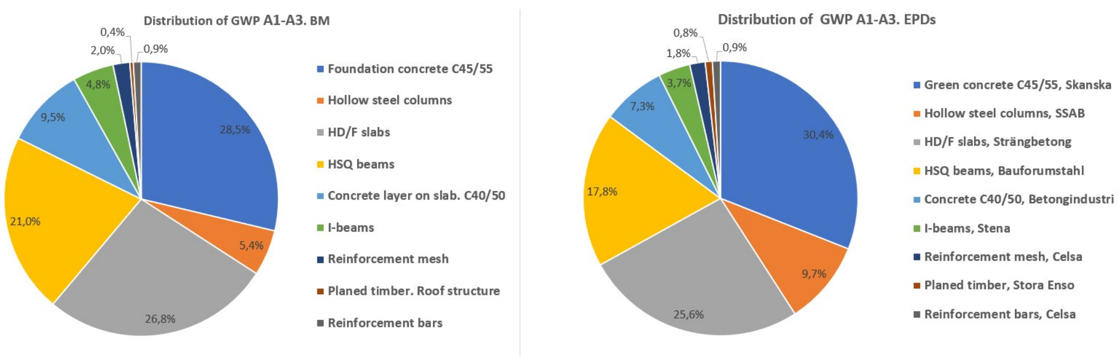

Figure 7.2: *GWP during the product stage of the structural system. The potential is divided into impact by structural element. Left diagram shows results with data given by BM and right diagram shows results for the same elements with EPD data.*

7.2 System 2: Steel column and beam system with filigree concrete slabs

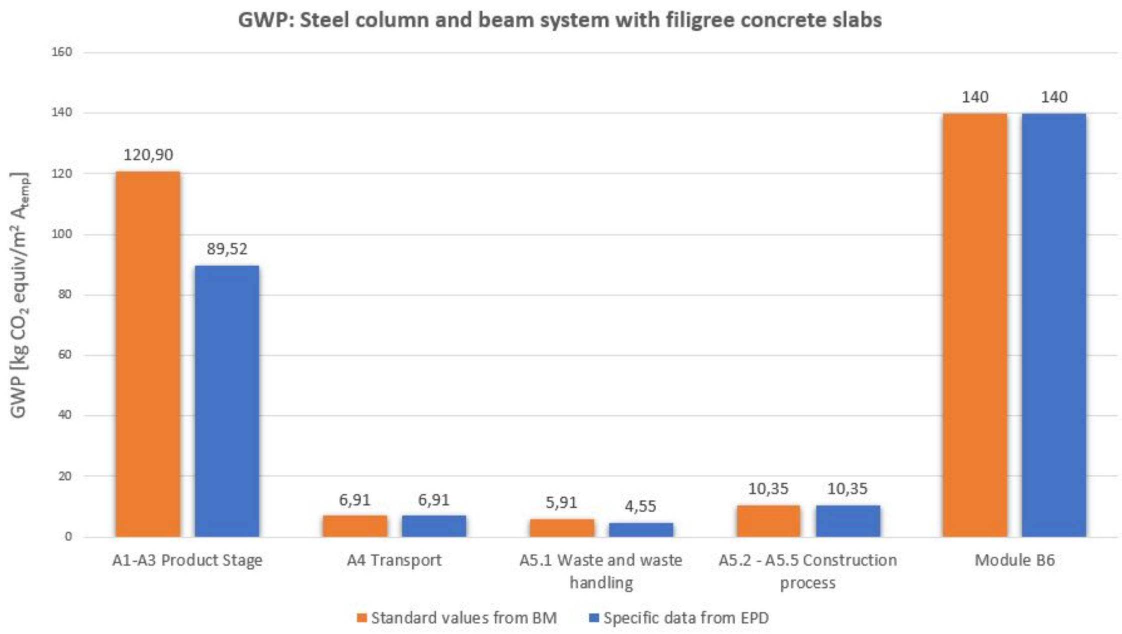

Figure 7.3: *GWP as result of generic values from BM (orange) and data from material specific EPD:s (blue). The potential is divided into modules where B6, operational energy use, is identical for both cases.*

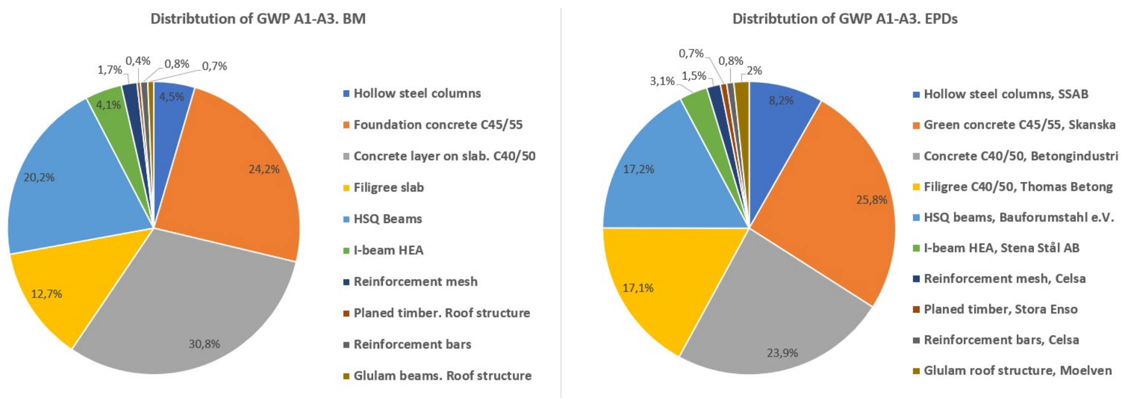

Figure 7.4: *GWP during the product stage of the structural system. The potential is divided into impact by structural element. Left diagram shows results with data given by BM and right diagram shows results for the same elements with EPD data..*

7.3 System 3: Steel column and beam system with CLT slab

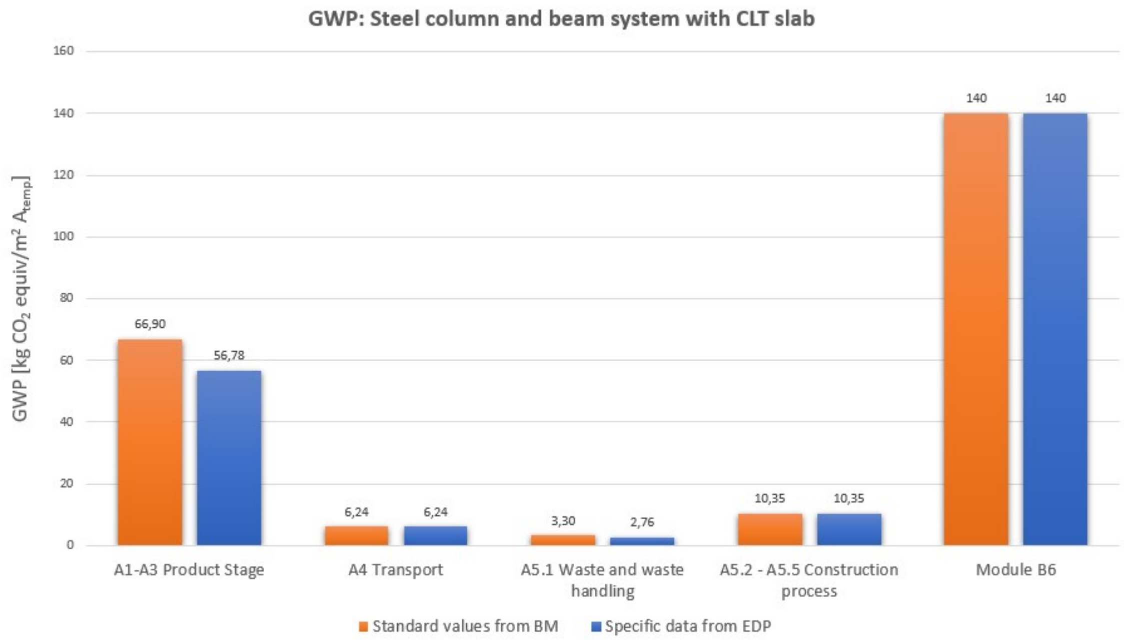

Figure 7.5: *GWP as result of generic values from BM (orange) and data from material specific EPD:s (blue). The potential is divided into modules where B6, operational energy use, is identical for both cases.*

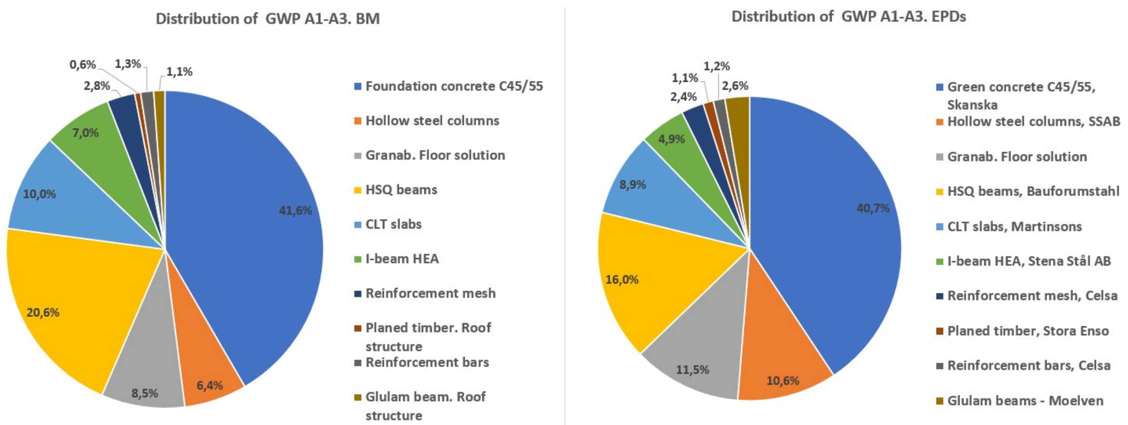

Figure 7.6: *GWP during the product stage of the structural system. The potential is divided into impact by structural element. Left diagram shows results with data given by BM and right diagram shows results for the same elements with EPD data.*

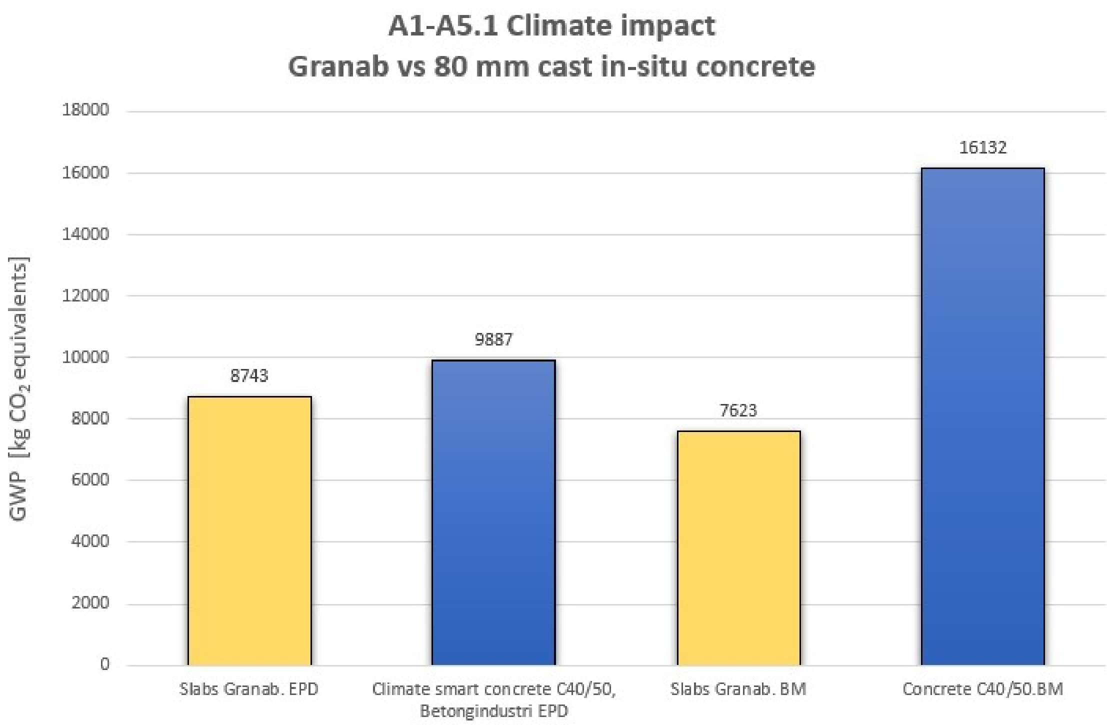

Figure 7.7: *Climate impact comparison between the granab solution used for the slabs in system 3 and using a 80 mm concrete slab. The comparison is based on the impact from the product stage of the products and shows result for EPD and BM values.*

7.4 System 4: Glulam column and beam system with prefabricated glulam modules

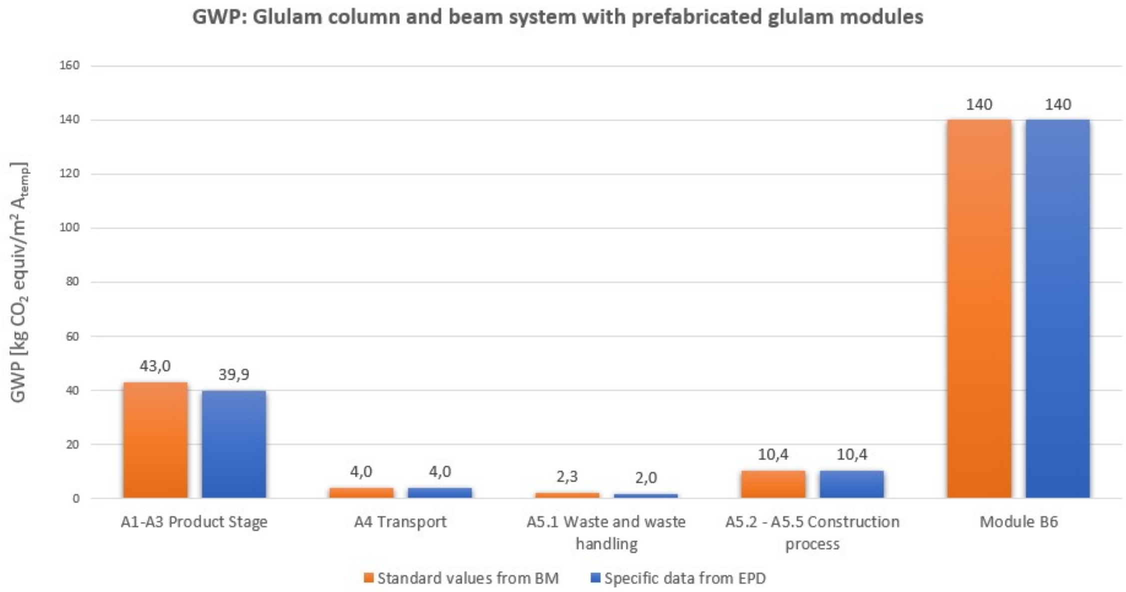

Figure 7.8: *GWP as result of generic values from BM (orange) and data from material specific EPD:s (blue). The potential is divided into modules where B6, operational energy use, is identical for both cases.*

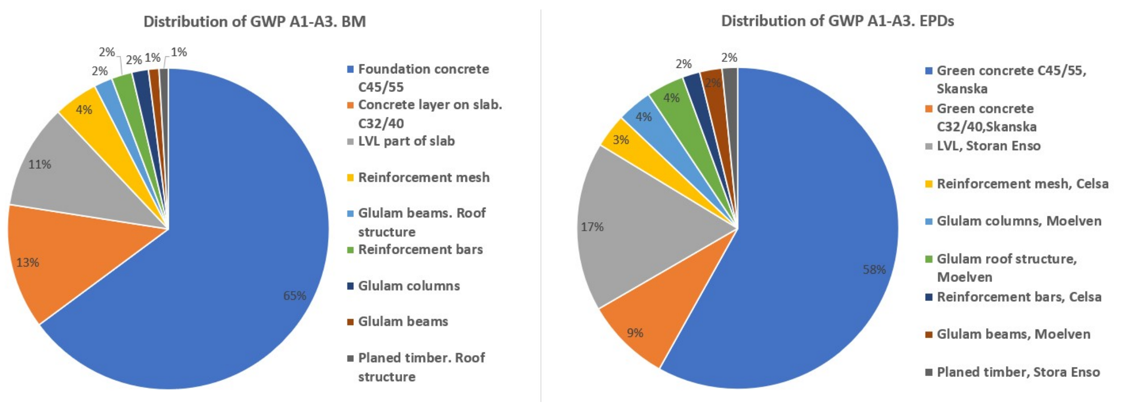

Figure 7.9: *GWP during the product stage of the structural system. The potential is divided into impact by structural element. Left diagram shows results with data given by BM and right diagram shows results for the same elements with EPD data.*

7.5 Summary of results for the four chosen structural systems

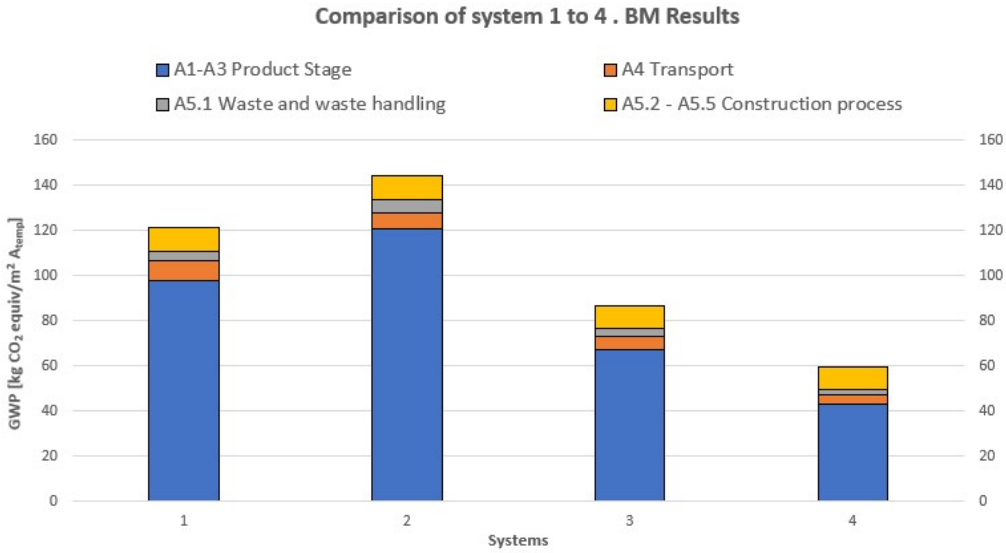

Figure 7.10: *Comparison of the total global warming potential between the four different structural systems, with GWP values acquired from BM.*

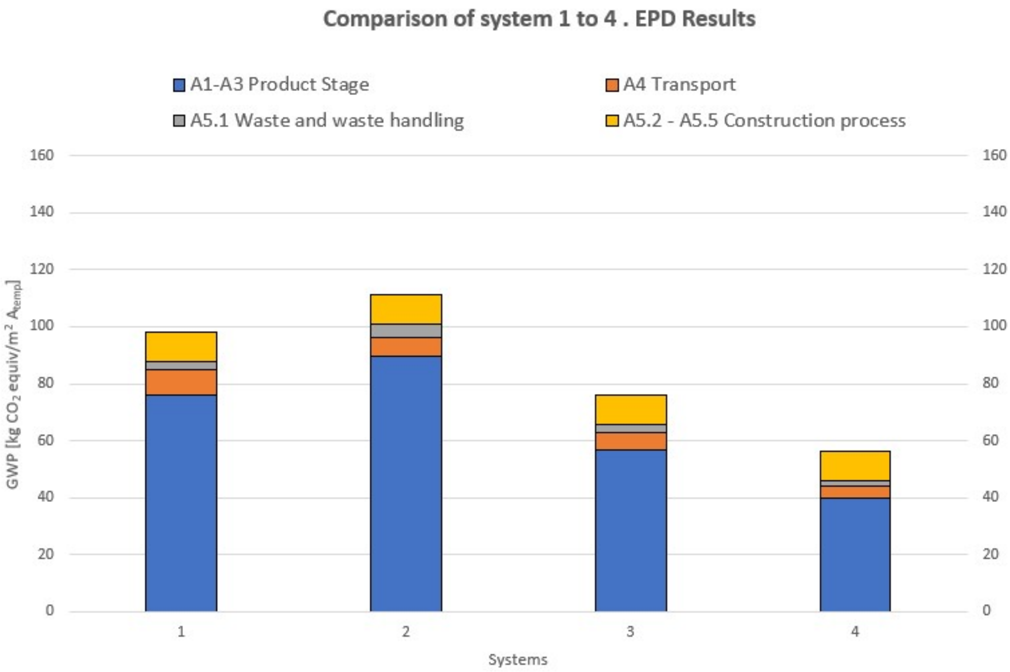

Figure 7.11: *Comparison of the total global warming potential between the four different structural systems, with GWP values aquired from product specific EPD:s.*

8

Discussion

This chapter brings up discussion points that are products of the way that the study was conducted and of the results obtained.

This study has used an analysis period equal to 50 years. The particular reason for this chosen period of time is that all the elements studied in the report are members of the structural systems and are complicated to replace under renovation circumstances. Boverket, 2020 states that a period of 50 years is in line with the need for extensive renovations in buildings. This is the reason why only the sub-module B6 of the module B is analysed in the report. In this case, a longer period of time would create uncertainties about the change of elements and less precise climate impact calculations for the elements studied. It is although important to have in mind that the analysis period established in this report is not the same as the expected life time of the buildings. An analysis period longer than 50 years could in addition to the above mentioned issues, also result in many uncertainties concerning the calculation of future emission scenarios and production methods (Boverket, 2020).

Module C of the life cycle assessment of the buildings was not evaluated in this report. The reason behind this is the lack of information concerning the climate impact from the deconstruction of buildings along with the waste processing and disposal. Erlandsson and Pettersson, 2015, stated the magnitude of the energy usage due to deconstruction of buildings in their report. The factors stated are although developed considering complete buildings and use the unit kWh/ton which implicates the use of another factors to convert the unit to $CO_2 - equivalents$ depending of the type of energy used.

The above mentioned method to convert the energy usage under the deconstruction of the structural systems was rejected in this report for the reasons that the method considers the entire buildings which would lead to conservative results. The results would be uncertain in addition to this since Erlandsson and Pettersson, 2015, only consider diesel and electricity while in reality there are several fuel and energy sources that might be used. This report recognizes the lack of information in this topic and the need of more analysis to achieve more precise life cycle assessments in the future.

The climate impact of the construction process, A5.2 to A5.5, shown in the results was calculated by Skanska's climate experts for the reference building in the project *ABCD-preschools*. This value of 10.35 CO_2-equivalents/$m^2 A_{temp}$ is conservative knowing that it was developed to analyse the complete reference building. This is not the case in this report where only the structural systems of the buildings were studied. On the other hand, this conservative approach makes it possible to use the value generally for all structural systems as it creates room for the differences that the structural systems' construction processes might have.

IVL, 2020, has also established a standard value that could have been used for these sub-modules. The value is 30 $CO_2 - equivalents/m^2A_{temp}$ and utilizes, as the method above, A_{temp} to calculate the impact from complete buildings. The results would in that case be even more conservative than the results obtained with the value utilized in this report and for that reason misleading for all the structural systems studied.

The software *Byggsektorns Miljöberäkningsverktyg* has been a crucial tool that has played a key role in the majority of the calculations made in this study. It is created in such way so that the user can utilize the generic data that is pre-installed in the program or the user-added input to analyze the climate impact of different materials and elements. Both of these scenarios have been analyzed for the impact A1-A3 in this report and they have shown that data from EPD.s generally generates lower climate impact than the generic data in BM.

The general result mentioned above should be interpreted carefully as the difference in GWP between generic values and data from EPD:s can differ by a great extent both negative and positive, as shown in Table 3.1. It is more correct to evaluate the building elements' EPD:s and their relevance firstly and then decide if they should be utilized to obtain the correct climate impact for each building element.

When conducting this thesis, some difficulties have been encountered regarding calculations of climate impact. To make the procedure of an LCA smoother, simplifications when calculating the climate impact contribution from module B and module C would be of great benefit. Finding information about all conceivable processes that are needed to construct buildings are somewhat difficult, as well as finding pertinent conversion factors from energy sources to GWP or standardized GWP values for certain LCA modules. Solving these issues would make the procedure more accessible which could make more people or companies conduct LCA:s of their projects. BM is a great example of this, since it is created by IVL and can be used by the entire construction industry even if it only considers module A. To have standardized methods for calculating would increase the relevance in comparing different studies between each other.

8.1 Discussion based on LCA results

As seen in the Result chapter, the LCA modules that dominate the climate impact are module A1-A3 (Product stage) and module B6 (Operational energy use). This is no surprise since module B6 spans over a period of 50 years and module A1-A3 consists of the production of all materials. The concrete ground slab is the largest contributor in all systems except system 2, but it really stands out in system 4.

Even if system 4 mostly consists of timber, the concrete ground slab stands for as much as 58-65% of its entire climate impact. Besides the foundation, the floor slabs are generally the structural members that stands for the largest climate impact.

The system that generates the lowest climate impact is system 4, which consists almost entirely of timber. Compared to the worst system, which is system 2, system 4 has almost 59% lower climate impact generated from module A according to the results based on generic values from BM. This difference highlights the magnitude of the climate impact from system 2 which is even larger than the impact from the building's energy usage, B6.

If system 1 and system 3 are compared, two systems that have the major difference of using concrete hollow core slabs and CLT floor slabs respectively, the results show that system 3 has 28% less climate impact from module A based on the results from generic values from BM.

In general, it is clear that the structural members that consist of concrete stand for the largest part of a system's climate impact due to the large volumes of concrete that are needed. Steel is on the other hand the material with the highest GWP/kg, but the total weight of steel in the systems are considerably lower than the weight of concrete. Hence, it is generally recommended to not only be conscious of the GWP/kg-factor but also be aware of the total mass used for each material.

8.1.1 Transportation

The impact from the transportation of the materials to the construction site, A4, was calculated with the generic transportation data for each material given by BM. The data includes both the distance traveled and the impact from the fuel that has been used under the transportation. This method of calculation was chosen to achieve a result that could represent future preschools in any city in Sweden.

Still, the previous knowledge that the generic data does not always reflect the reality accurately could also apply for the transport data. An advise is that new analysis are carried out in the future when manufacturers and specific building places are established which will give a more precise transportation impact. This will however only have a small effect on the total climate impact from the product stage of the building. The results show that A4 is between five and nine percent of the climate impact from module A.

8.1.2 Relevant comparisons

A comparison between the total climate impact from the reference building and the portion that the reference structural system stands for have been implemented and is shown below. This have been made to see how large part the structural system stands for of the climate impact generated from the entire building. Another interesting comparison is the one between different solutions used to improve the acoustic behaviour of timber floor slabs. In this study a comparison between the Granab floor and a concrete layer casted on top of the CLT slab in system 3 has been conducted, with the results showed below.

8.1.2.1 Comparison between the total climate impact from the reference building and impact from its structural system

This report focuses on the structural system of the preschool called concept C in the project *ABCD preschools*. The climate impact from this part of the building is however only a portion of the total impact that the complete building including the ground and all non-bearing elements has on the environment. A comparison of the obtained results regarding the reference building's structural system and the results from a previous climate calculation made by experts on the same whole building is presented in Table 8.1.

Table 8.1: *Climate impact as a result of the product stage of the entire preschool, the structural system with data from BM and the structural system with EPD data.*

	Climate impact A1-A5 [kg CO2e]	**Portion of the total climate impact of the building**
Entire building	261	100%
Structural system. EPD	98	37,5%
Structural system. BM	121	46,4%

Table 8.1 shows that the structural systems' impact is up to almost half of the impact of the entire building and proves that the structural system is a major contributor to the total climate impact that the preschool has. This indicates that the material choices made for the structural systems will lead to a large effect on the total climate impact from the building's product stage.

8.1.2.2 Comparison of climate impact between Granab floor and concrete casting

Results from the comparison of climate impact between the Granab floor used in system 3 and a concrete casting show that a large reduction on GWP can be achieved if Granab floor are used instead of concrete. The solution of a floor with concrete casting was obtained from the *CLT handbook* by SvensktTrä, 2017, which consists of a CLT slab of 230 mm, 30 mm insulation, and 80 mm concrete casted on top. This solution achieves the requirements of sound class C, but it is possible to improve this to achieve even better performance regarding this. The comparisons made in this study is only between the concrete layer and the Granab floor, excluding insulation, and have been performed using both generic values from BM and product specific EPD values.

In the comparison using BM values, there is a significant difference in GWP between the solutions, with an improvement by as much as 53 percent. Using product specific EPD values does not generate the same massive improvement, but a solid improvement of 12 percent is achieved. The results and improvements can be seen in Table 8.2 presented below.

Table 8.2: *Resulting climate impact for Granab floor and concrete screed for both BM and EPD values. The table also shows the percentage of GWP reduction that can be achieved if the Granab solution is used.*

	Total climate impact module A1-A5.1 [kg CO2]	**Reduced climate impact [%]**
Granab floor, BM	7623	53
Concrete screed, BM	16132	
Granab floor, EPD	8743	12
Concrete screed, EPD	9887	

The big difference between the two cases are mainly because of the use of climate smart concrete in the case where EPD values are used. This further confirms the great benefits of using climate smart concrete instead of traditional concrete, regarding climate impact. However, another great benefit of using Granab floor or similar solutions, beside the climate impact reduction, is the possibility to place installations inside the floor structure. This could allow a reduction of the floor thickness, which can be an issue with timber constructions.

8.2 Potential improvements

This report has shown that the material choice of the structural elements in the buildings has a major effect on the resulting climate impact from the preschools analyzed. Green alternatives such as Skanska's green concrete and scrap-based steel showed the ability to generate large improvements in the climate impact studied. Therefore, the buildings materials' constant development is an aspect that must be expected and the implementation of these should be initiated to accomplish lower climate impacts.

Green concrete is a climate smart concrete developed by Skanska that is produced using high slag proportions in the concrete mixture which leads to a lower proportion of cement and in turn to a lower climate impact. The improvement that comes using this type of concrete compared to concrete from betongindustri is 40% as shown in Table 3.1 and has the potential to be as much as 50% according to Skanska, 2021a. The concrete is also said to meet the same requirements concerning durability, strength, life span and castability as Skanska's normal concrete. The concrete was launched in the first half of 2019 and made a "climate smart success" according to Betong.se, 2019. Green concrete is between 5% to 8% more expensive than traditional concrete that can lead to a large economical difference in many projects, but green concrete is sometimes stronger than traditional concrete. In that case the concrete strength class to use in the projects can be reduced which can lead to the green concrete being even more economically efficient than others (Skanska, 2020). Skanska's green concrete is only available for a specific number of cities in Sweden. However, other concrete companies in Sweden have similar green solutions in other parts of the country.

There are two methods to produce steel elements. The first is the most climate tense which is when the steel is manufactured with iron ore and the second with scrap-based steel recycled from no longer used steel. According to SSAB, 2021, The demand for steel is at the moment handled with 30% scrap-based steel and should be handled by 50% the year 2050. The opportunities to reduce the climate impact coming from steel are limited, product and energy efficiency are other improvements that would favor the environment beside using scrap-based steel SSAB, 2021. But even if an increase use of scrap-based steel would be reality, the only way to provide enough steel to handle the demand is using iron ore. SSAB, LKAB and Vattenfall are for this reason collaborating to develop "Hydrogen Breaktrough Ironmaking Technlogy", called HYBRIT, so that the production of iron ore based steel can continue in a more environmental friendly way. This would result in SSAB being the first steel company in the world to supply fossil-free steel the year 2026.

It is, in many ways, possible to reduce the climate impact that the building process stands for in a building's life cycle. Green concrete and scrap based steel are clear examples of that, but transport scenarios can also impact the total GWP generated by a building. Customize transportation for each unique building project to reduce the distance between the building site and material suppliers, as well as choosing renewable fuel for transportation could have a large impact on GWP generated from transports. These solutions are already available on the market today, but are still not used in a sufficient extent. If the climate goals set, to reach zero CO_2-emissions year 2045 are going to be achieved, the construction industry needs to both use the technology available today to a larger extent, but also keep providing new innovations that will reduce the climate impact. This is illustrated by Figure 8.1, where real data is used until year 2015 and a scenario to achieve zero CO_2-emissions is used after 2015.

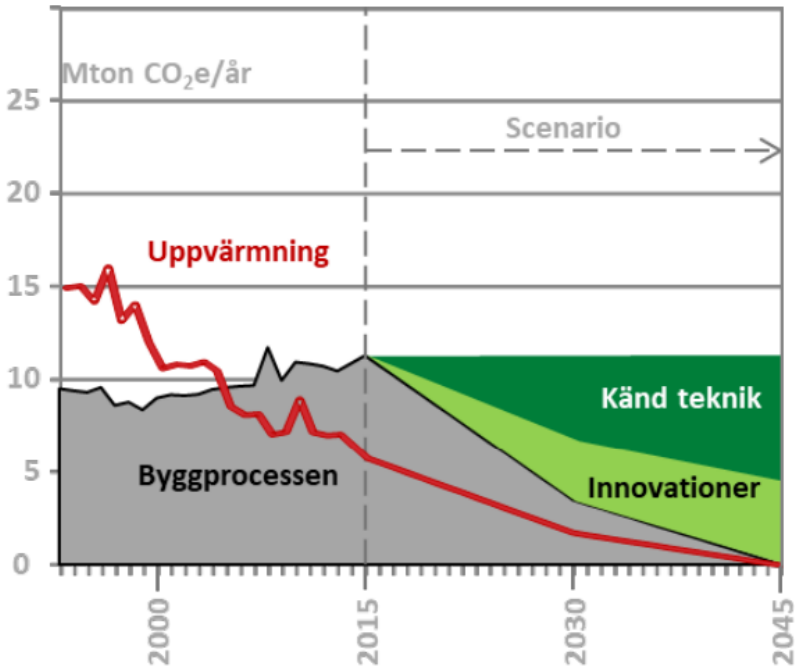

Figure 8.1: *Yearly CO_2 emissions coming from heating (red line) and from the construction process of buildings (black line). The figure illustrates how known technology and upcoming innovations could be used to reduce the total emissions. Erlandsson et al., 2017*

8.3 CO_2 storage in timber

Timber is a popular building material not only for its aesthetics but also for its ability to store carbon dioxide from the air. Both the growing forests and their products like timber and paper possess this ability. During the time that timber being used it could store approximately 0.9 metric tons of carbon dioxide until its life cycle ends as stated by SvensktTrä, 2015. Taking this into consideration in this study would impact the results heavily since the timber products' GWP will be reduced to even negative magnitudes which would imply that the products have a positive impact on the climate and outwork the negative impact from disforestation, transportation and manufacturing. The reason that this is not included in the LCA of the structural systems is because even if the timber stores a high amount of carbon dioxide, the same amount will be released into the atmosphere as soon as its life cycle ends.

This is an important topic to highlight considering that the more timber that is used, the more carbon dioxide from the atmosphere are stored inside the material. It is a process that can be managed environmentally smart if the felled threes are made up by planting new ones. Sweden is an example of this, where 120 millions of cubic meter forest grows each year and only 75% of them are felled according to Sveaskog, 2015. Figure 8.2 illustrates the CO_2 storage capacity of wood compared to yearly every day emissions.

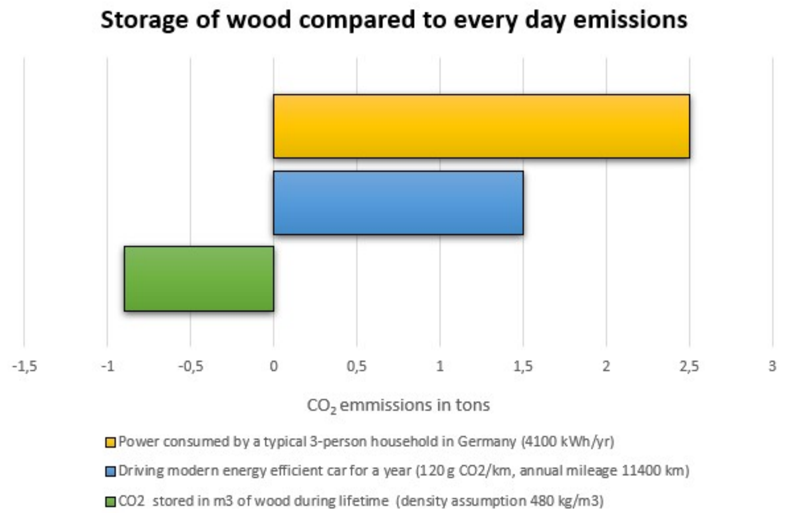

Figure 8.2: *Carbon dioxide storage of a cubic meter wood compare to yearly emissions caused by human activities (van der Lugt, 2020).*

8.4 Generalization of the results

The results of this thesis are meant to be used in the conceptual design phase of a building, in order to simplify and help the decision of the structural system in a preliminary stage of a project. The use of these results will include environmental aspects in such decisions which in many cases are excluded or not considered at this stage.

The generated results from this analysis correspond entirely to the structural systems analyzed in this report. These systems are in turn developed to suit the preschool buildings in the project *ABCD-preschools*. The results may however be implemented to other educational buildings or similar buildings where comparable structural systems are used as for instance office- and residential buildings.

The data used to obtain the results in this study is material specific data together with generic material and transportation values. This indicates that the results are very much general for all kind of structures besides the fact that the structural systems are developed for preschool buildings. It is therefore recommended to use the outcome of this report as a complement to make comparisons, conclusions and assumptions for any structural system that utilize resembling building materials as this thesis. An environmental scale will be introduced in the continuation of this chapter. This scale is, as mentioned previously, a tool to be used in future analyzes.

8.4.1 Environmental design factor

Figure 8.3 shows the performance regarding climate impact of every system in a scale from 0% to 50% for the EPD and the BM cases. The percentages represent how large a system's variable climate impact in this analysis (i.e. the impact from the modules that are not identical for all systems) is in relation to each system's total climate impact. For this reason, a smaller percentage in the scale represents a more climate friendly structural system according to the results in this study.

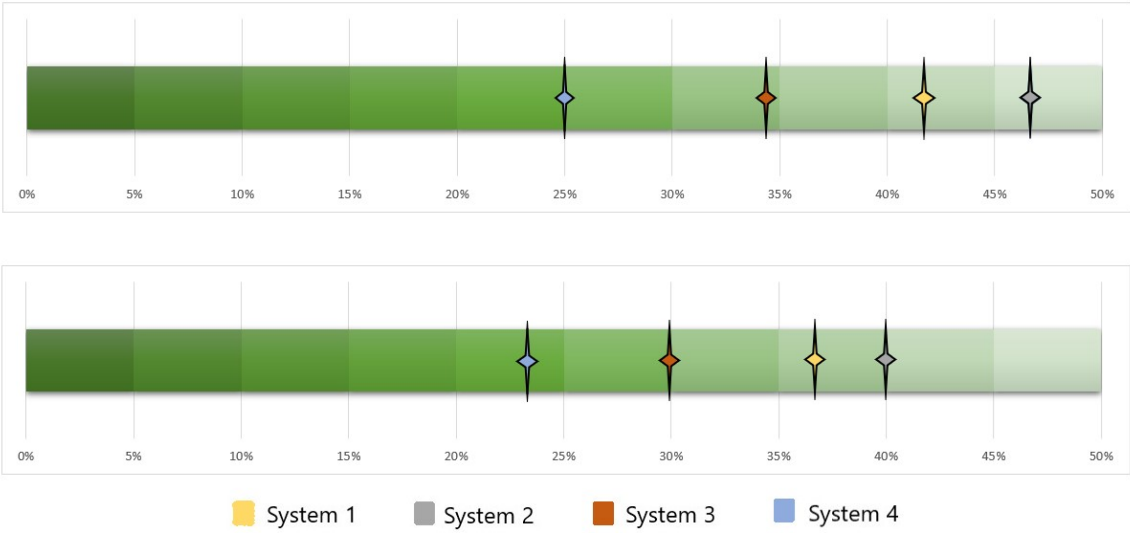

Figure 8.3: *The unique climate impact from system 1 to 4 in relation to the total climate impact from each system. the top graph represents BM-results and the bottom graph the EPD-results.*

System 1, which is the reference system used by the project *ABCD preschools* turned out to perform better than system 2 but worse than system 3 and system 4. Those systems, with more use of timber members, showed better climate results and the system made completely out of glulam stands out, having a percentage equal to and below 25% in the BM and EPD cases respectively. This can be compared to system 2 which scored 47% and 40% mostly because of its large use of concrete in combination with steel beams and columns.

The purpose of Figure 8.3 is to illustrate the climate impact of the structural systems studied so that future project developers can get a brief but accurate overview of the impact that these type of systems have on the climate. The graph is not developed to be a substitute for an LCA analysis but to operate as an indicator and point of comparison for various structural systems. Because of this, the graph has the potential to lead to wiser decision-making in early stages such as the conceptual design phase.

9
Conclusion

The results from this study confirm that the structural system stands for a large part of a building's climate impact over an analysis period of 50 years. However, there are substantial differences between the different structural systems with as much as 59% less CO_2-equivalents generated from the best performing system compared to the worst.

The system that performed best in this study was system 4, followed by system 3, system 1 and lastly, system 2. System 2 even has a higher climate impact from the product stage and construction process stage (module A) than the operational energy use (module B6) over 50 years.

9.1 Concluding recommendations

The recommendations based on the results of this study are summarized and stated below:

- There are different structural solutions that can be implemented in all systems, with potential to decrease the climate impact, like the Granab solution instead of a concrete screed on top of a CLT slab. These potential improvements regarding climate impact, together with optimization regarding material choices can make a massive difference in the end. It is up to the construction industry to embrace innovations to achieve the set climate goals.

- As mentioned in the discussion, the structural members with concrete are in general the worst regarding climate impact. But at the same time, concrete has the potential to stand for the largest reduction in GWP if green concrete is used instead of traditional concrete. That reduction can be massive for structural systems that utilize a large amount of concrete, why it is highly recommended to use green concrete if possible. It may be slightly more expensive but it has other advantages besides the climate impact.

- There is a great importance in implementing life cycle assessments in an early stage of every construction project. The LCA will highlight the processes and structural members with the largest climate impact and lead to potential improvements.

- Transportation of materials to the building site has an impact on the climate that is not large but by any means remarkable in relation to the total climate impact from the buildings. This can be optimized by using materials with short transport distances.

- There is a lot to gain by using EPD:s for certain products that are used in a building. By comparing the same product from different companies, it is possible to choose the one that are most suitable for each project. Differences between product specific EPDs show that even the same materials can differ a fair amount in GWP between manufacturers.

- The simplified Figure 8.3 is an accurate illustration of the climate impact that the studied structural systems generate. It has the purpose to work as an indicator for future projects when other structural systems are evaluated but should however not be used as a substitute for other LCA analysis.

- Timber owns the special ability to store carbon dioxide. This should not be accounted in an LCA analysis nor should its potential be overseen by any means under material considerations .

9.2 Further studies

This study focuses on module A of the LCA, and to achieve a more complete analysis at least module C (end of life stage) should be considered. At the same time, there are uncertainties about climate impact generated from module C as mentioned in the Discussion and additional studies are necessary to verify the calculations of climate impact from module C.

Regarding module B (use stage), this study only considers the operational energy usage (B6), which was found most relevant for this thesis. However, if an entire building and not only the structural system is analysed, module B would be more of interest. Especially if the analysis period is extended to 100 years, since many parts of the building will then need maintenance and replacement.

It is of high importance to continue with studies that investigate the climate impact from buildings. Especially since there are many ways to conduct life cycle assessments and that a building project can be entirely different from another. To widen the knowledge, studies that consider different materials, different building types, different LCA modules, entire buildings or parts of buildings need to be executed to establish a more solid database.

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A
Preliminary sizing calulations

A.1 System 2. Calculations

System 2: Steel column and beam system with filigree concrete slabs

Beams

Hat-beams HSQ - Mid beam

$t_{öf.2} := 50mm$ $b_{öf.2} := 100mm$ $t_{w.2} := 8mm$ $h_{w.2} := 220mm$ $f_{yd} := 235MPa$

$t_{uf.2} := 30mm$ $b_{uf.2} := 300mm$ $a := 4mm$ $E_{steel} := 210GPa$

$L_h := 6m$ $b_h := (6.646 + 5.165) \cdot m = 11.811\,m$

$A_{golv.m} := b_h \cdot L_h = 70.866\,m^2$ $\alpha_{A.mid} := 0.5 + \frac{10m^2}{A_{golv.m}} = 0.641$

$$\varepsilon := \sqrt{\frac{235MPa}{f_{yd}}} = 1$$

$$q_{imp} := 3\,\frac{kN}{m^2}$$

$$f_{fb.2} := \frac{b_{uf.2}}{2} - \frac{b_{öf.2}}{2} - t_{w.2} - a = 88 \cdot mm$$

$$Q_k := \frac{q_{imp} \cdot b_h}{2} = 17.716 \cdot \frac{kN}{m}$$

$\frac{b_{öf.2}}{t_{öf.2}} = 2$ < 38ε för tväsnittsklass 2

$\frac{f_{fb.2}}{t_{uf.2}} = 2.933$ < 10ε för tvärsnittsklass 2

$$y_{tp.2} := \frac{t_{öf.2} \cdot b_{öf.2} \cdot \left(\frac{t_{öf.2}}{2}\right) + 2 \cdot t_{w.2} \cdot h_{w.2} \cdot \left(7mm + \frac{h_{w.2}}{2}\right) + t_{uf.2} \cdot b_{uf.2} \cdot \left(7mm + h_{w.2} + \frac{t_{uf.2}}{2}\right)}{t_{öf.2} \cdot b_{öf.2} + 2 \cdot t_{w.2} \cdot h_{w.2} + t_{uf.2} \cdot b_{uf.2}} = 154.957 \cdot mm$$

$$W_{pl.2} := b_{öf.2} \cdot t_{öf.2} \cdot \left(y_{tp.2} - \frac{t_{öf.2}}{2}\right) + 2 \cdot h_{w.2} \cdot t_{w.2} \cdot \left[y_{tp.2} - \left(7mm + \frac{h_{w.2}}{2}\right)\right] \ldots = 1.567 \times 10^{6} \cdot mm^{3}$$
$$+ b_{uf.2} \cdot t_{uf.2} \cdot \left(7mm + h_{w.2} + \frac{t_{uf.2}}{2} - y_{tp.2}\right)$$

$$\rho_{concrete} := 2350 \frac{kg}{m^{3}} \qquad \rho_{steel} := 7800 \frac{kg}{m^{3}}$$

$$t_{slab.2} := 300mm$$

$$G_{beam.2} := \rho_{steel} \cdot g \cdot \left(t_{öf.2} \cdot b_{öf.2} + 2 \cdot t_{w.2} \cdot h_{w.2} + t_{uf.2} \cdot b_{uf.2}\right) = 1.34 \cdot \frac{kN}{m}$$

$$G_{slab.2} := \rho_{concrete} \cdot t_{slab.2} \cdot g \cdot \frac{b_h}{2} = 40.829 \cdot \frac{kN}{m}$$

$$M_{max.b2} := \left[1.35 \cdot \left(G_{beam.2} + G_{slab.2}\right) \cdot 0.0772 + 1.5 \cdot Q_k \cdot \alpha_{A.mid} \cdot 0.0996\right] \cdot L_h^{2} = 219.304 \cdot kN \cdot m$$

$$M_{pl.Rd.2} := W_{pl.2} \cdot f_{yd} = 368.193 \cdot kN \cdot m$$

$$\boxed{M_{uti.2} := \frac{M_{max.b2}}{M_{pl.Rd.2}} = 59.562 \cdot \%}$$

Shearforce Capacity

$$V_{Rd.2} := \frac{2 \cdot t_{w.2} \cdot h_{w.2} \cdot f_{yd}}{\sqrt{3}} = 477.584 \cdot kN$$

$$V_{max.2} := 1.35 \cdot \left(G_{slab.2} + G_{beam.2}\right) \cdot (0.6071 + 0.5357) \cdot L_h \ldots = 515.375 \cdot kN$$
$$+ 1.5 \cdot Q_k \cdot \alpha_{A.mid} \cdot (0.6205 + 0.6026) \cdot L_h$$

$\eta := 1.2$ Dependent on steel class

$$\begin{cases} \text{"Need for further checks"} & \text{if } \dfrac{h_{w.2}}{t_{w.2}} \geq 75 \cdot \dfrac{\varepsilon}{\eta} \\ \text{"No need for further checks"} & \text{otherwise} \end{cases} = \text{"No need for further checks"}$$

$$V_{uti.2} := \frac{\dfrac{V_{max.2}}{2}}{V_{Rd.2}} = 53.956 \cdot \%$$

Deflection:

$L_h = 6\,m$ Calculating for the worst case with three spans of 6 meters

$t_{öf.2} := 50mm$ $b_{öf.2} := 100mm$ $t_{w.2} := 8mm$ $h_{w.2} := 220mm$

$t_{uf.2} := 30mm$ $b_{uf.2} := 300mm$ $a := 4mm$ $E_{steel} := 210GPa$

$h_{tot} := t_{uf.2} + h_{w.2} + 7mm = 257 \cdot mm$ $y_{tp.2} = 0.155\,m$ $\psi_2 := 0.6$

$$I_{tot.2} := \frac{b_{uf.2} \cdot t_{uf.2}^{\,3}}{12} + b_{uf.2} \cdot t_{uf.2} \cdot \left(h_{tot} - y_{tp.2} - \frac{t_{uf.2}}{2}\right)^2 \ldots = 1.686 \times 10^{-4}\,m^4$$
$$+ 2\left[\frac{t_{w.2} \cdot h_{w.2}^{\,3}}{12} + t_{w.2} \cdot h_{w.2} \cdot \left(t_{öf.2} + \frac{h_{w.2}}{2} - y_{tp.2}\right)^2\right] + \frac{b_{öf.2} \cdot t_{öf.2}^{\,3}}{12} \ldots$$
$$+ b_{öf.2} \cdot t_{öf.2} \cdot \left(y_{tp.2} - \frac{t_{öf.2}}{2}\right)^2$$

$$Q_{sls.perm} := (G_{beam.2} + G_{slab.2}) = 42.169 \cdot \frac{kN}{m}$$

$$Q_{sls.var} := Q_k = 17.716 \cdot \frac{kN}{m}$$

$$\frac{L_h}{300} = 20 \cdot mm$$ requirement for permanent load

$$\frac{L_h}{400} = 15 \cdot mm$$ requirement for variable load

$$v_{perm} := \frac{0.99 \cdot Q_{sls.perm} \cdot L_h^{\,4}}{100 \cdot E_{steel} \cdot I_{tot.2}} = 15.278 \cdot mm$$

$$v_{var} := \frac{0.99 \cdot Q_{sls.var} \cdot L_h^{\,4}}{100 \cdot E_{steel} \cdot I_{tot.2}} = 6.419 \cdot mm$$

$$v_{tot} := v_{perm} + v_{var} \cdot \psi_2 = 19.129 \cdot mm$$

$$\boxed{\delta_{util.perm} := \frac{v_{perm}}{\frac{L_h}{300}} = 76.389 \cdot \%}$$

$$\boxed{\delta_{util.var} := \frac{v_{var} \cdot \psi_2}{\frac{L_h}{400}} = 25.675 \cdot \%}$$

$$\boxed{\delta_{util.tot} := \frac{v_{tot}}{\frac{L_h}{300}} = 95.646 \cdot \%}$$

One sided HSQ - beam . Edge beam

$$L_h := 6m \qquad b_h := \left(\frac{6.646}{2}\right) \cdot m = 3.323\,m$$

$f_{yd} := 235MPa$ $\varepsilon := \sqrt{\frac{235MPa}{f_{yd}}} = 1$ $S_3 := 3 \cdot 0.8 \frac{kN}{m^2}$

$t_{öf} := 50mm$ $b_{öf} := 69mm$ $t_w := 8mm$ $h_w := 210mm$

$t_{uf} := 30mm$ $b_{uf} := 175mm$ $a := 4mm$

$g_{eg} := \rho_{concrete} \cdot t_{slab.2} \cdot g = 6.914 \cdot \frac{kN}{m^2}$

$f_{fb} := \frac{b_{uf}}{2} - \frac{b_{öf}}{2} - t_w - a = 41 \cdot mm$ $\rho_{steel} := 7800 \frac{kg}{m^3}$

$\frac{b_{öf}}{t_{öf}} = 1.38$ < 38ε för tväsnittsklass 2

$\frac{f_{fb}}{t_{uf}} = 1.367$ < 10ε för tvärsnittsklass 2

$$y_{tp} := \frac{t_{öf} \cdot b_{öf} \cdot \left(\frac{t_{öf}}{2}\right) + 2 \cdot t_w \cdot h_w \cdot \left(7mm + \frac{h_w}{2}\right) + t_{uf} \cdot b_{uf} \cdot \left(7mm + h_w + \frac{t_{uf}}{2}\right)}{t_{öf} \cdot b_{öf} + 2 \cdot t_w \cdot h_w + t_{uf} \cdot b_{uf}} = 139.351 \cdot mm$$

$$W_{pl} := b_{öf} \cdot t_{öf} \cdot \left(y_{tp} - \frac{t_{öf}}{2}\right) + 2 \cdot h_w \cdot t_w \cdot \left[y_{tp} - \left(7mm + \frac{h_w}{2}\right)\right] \ldots = 9.728 \times 10^5 \cdot mm^3$$
$$+ b_{uf} \cdot t_{uf} \cdot \left(7mm + h_w + \frac{t_{uf}}{2} - y_{tp}\right)$$

$M_{pl.Rd} := W_{pl} \cdot f_{yd} = 228.612 \cdot kN \cdot m$

$b_h = 3.323\,m$ $L_h = 6\,m$

$A_{golv.m} := (6.446m) \cdot L_h = 38.676\,m^2$

$\alpha_{A.edge} := 0.5 + \frac{10m^2}{A_{golv.m}} = 0.759$

$\varphi_{0.imp} := 0.7 \qquad \varphi_S := 0.8$

$g_{eg} = 6.914 \cdot \frac{kN}{m^2} \qquad G_{eg} := 0.152\frac{kN}{m^2} \qquad S_3 = 2.4 \cdot \frac{kN}{m^2} \qquad Q_w := 0.322\frac{kN}{m^2} \qquad \varphi_w := 0.3$

$Q_k := q_{imp} \cdot \frac{(6.446m)}{2} = 9.669 \cdot \frac{kN}{m} \qquad G_{slab} := g_{eg} \cdot \frac{(6.446m)}{2} = 22.283 \cdot \frac{kN}{m}$

$G_{s.balk} := \rho_{steel} \cdot g \cdot \left(t_{öf} \cdot b_{öf} + 2 \cdot t_w \cdot h_w + t_{uf} \cdot b_{uf}\right) = 0.922 \cdot \frac{kN}{m}$

$M_{max.balk} := \left[1.35 \cdot \left(G_{slab} + G_{s.balk}\right) \cdot 0.0772 + 1.5 \cdot Q_k \cdot \alpha_{A.edge} \cdot 0.0996\right] \cdot L_h^2 = 126.512 \cdot kN \cdot m$

$\boxed{M_{util} := \frac{M_{max.balk}}{M_{pl.Rd}} = 55.339 \cdot \%}$

Torsional capacity

$$x_{tp} := \frac{t_{öf} \cdot b_{öf} \cdot \left(\frac{b_{öf}}{2} + t_w\right) + t_w \cdot h_w \cdot \left(\frac{t_w}{2}\right) + t_{uf} \cdot b_{uf} \cdot \left(\frac{b_{uf}}{2}\right) + t_w \cdot h_w \cdot \left(t_w + b_{öf} + \frac{t_w}{2}\right)}{t_{öf} \cdot b_{öf} + 2 \cdot t_w \cdot h_w + t_{uf} \cdot b_{uf}} = 0.062\,m$$

$$e_x := \frac{b_{uf} - \left(b_{öf} + t_w \cdot 2\right)}{2} + \left(b_{öf} + t_w \cdot 2\right) - x_{tp} = 0.068\,m$$

$$Q_{edgeb} := 1.35 \cdot \left(G_{slab} + G_{s.balk}\right) + 1.5 \cdot Q_k \cdot \alpha_{A.edge} = 42.329 \cdot \frac{kN}{m}$$

$$Q_{ecc} := Q_{edgeb} \cdot e_x = 2.875 \cdot \frac{kN \cdot m}{m}$$

$$T_{ed} := \frac{Q_{ecc} \cdot (L_h)}{2} = 8.624 \cdot kN \cdot m$$

$$A_{med} := (b_{öf} + t_w) \cdot \left(h_w + \frac{t_{uf}}{2} + 7mm - \frac{t_{öf}}{2}\right) = 0.016 m^2$$

$$W_T := 2 \cdot A_{med} \cdot t_w = 2.55 \times 10^{-4} m^3$$

$$T_{Rd} := \frac{f_{yd} \cdot W_T}{\sqrt{3}} = 34.601 \cdot kN \cdot m$$

$$\boxed{T_{uti} := \frac{T_{ed}}{T_{Rd}} = 24.923 \cdot \%}$$

Shear capacity

$$V_{Rd.stålb} := \frac{2 \cdot t_w \cdot h_w \cdot f_{yd}}{\sqrt{3}} = 455.876 \cdot kN$$

$$V_{pl.T.Rd} := V_{Rd.stålb} \cdot \left(1 - \frac{T_{ed}}{\frac{f_{yd} \cdot m^3}{\sqrt{3}}}\right) = 455.847 \cdot kN$$

Reduction due to torsion and shear interaction

$$V_{max.stålb} := \frac{1.35 \cdot (G_{slab} + G_{s.balk}) \cdot (0.6071 + 0.5357) \cdot L_h \ldots + 1.5 \cdot Q_k \cdot \alpha_{A.edge} \cdot (0.6205 + 0.6026) L_h}{2} = 147.771 \cdot kN$$

$$V_{uti.sbalk} := \frac{V_{max.stålb}}{V_{pl.T.Rd}} = 32.417 \cdot \%$$

$$\begin{cases} \text{"Need for further checks"} & \text{if } \frac{h_w}{t_w} \geq 75 \cdot \frac{\varepsilon}{\eta} \\ \text{"No need for further checks"} & \text{otherwise} \end{cases} = \text{"No need for further checks"}$$

Beam deflection:

$L_h = 6\,m$ Calculating for the worst case with three spans of 6 meters

$h_{tot} := t_{uf} + h_w + 7mm = 247 \cdot mm$ $y_{tp} = 0.139\,m$

$$I_{tot.2} := \frac{b_{uf} \cdot t_{uf}^{3}}{12} + b_{uf} \cdot t_{uf} \cdot \left(h_{tot} - y_{tp} - \frac{t_{uf}}{2}\right)^2 \ldots + 2\left[\frac{t_w \cdot h_w^{3}}{12} + t_w \cdot h_w \cdot \left(t_{öf} + \frac{h_w}{2} - y_{tp}\right)^2\right] + \frac{b_{öf} \cdot t_{öf}^{3}}{12} \ldots + b_{öf} \cdot t_{öf} \cdot \left(y_{tp} - \frac{t_{öf}}{2}\right)^2 = 1.045 \times 10^{-4}\,m^4$$

$$Q_{sls.perm} := \left(G_{s.balk} + G_{slab}\right) = 23.205 \cdot \frac{kN}{m}$$

$$Q_{sls.var} := Q_k = 9.669 \cdot \frac{kN}{m}$$

$\frac{L_h}{300} = 20 \cdot mm$ requirement for permanent load

$\frac{L_h}{400} = 15 \cdot mm$ requirement for variable load

$$v_{perm} := \frac{0.99 \cdot Q_{sls.perm} \cdot L_h^{4}}{100 \cdot E_{steel} \cdot I_{tot.2}} = 13.572 \cdot mm$$

$$v_{var} := \frac{0.99 \cdot Q_{sls.var} \cdot L_h^4}{100 \cdot E_{steel} \cdot I_{tot.2}} = 5.655 \cdot mm$$

$$v_{tot} := v_{perm} + v_{var} \cdot \psi_2 = 16.965 \cdot mm$$

$$\boxed{\delta_{util.perm} := \frac{v_{perm}}{\frac{L_h}{300}} = 67.861 \cdot \%}$$

$$\boxed{\delta_{util.var} := \frac{v_{var} \cdot \psi_2}{\frac{L_h}{400}} = 22.621 \cdot \%}$$

$$\boxed{\delta_{util} := \frac{v_{tot}}{\frac{L_h}{300}} = 84.827 \cdot \%}$$

Beams

Columns

Steeel Columns VKR - Outer columns, mid wall - Level 1

$b_{sp.2} := 100mm$ $h_{sp.2} := 150mm$ $t_{sp.2} := 8mm$ $f_{yk} := 275MPa$ $L_p := 3.35m$

$S_3 := 3 \cdot 0.8 \frac{kN}{m^2}$ $Q_w := 0.322 \frac{kN}{m^2}$ $G_{eg} := 0.152 \frac{kN}{m^2}$ $E := 210GPa$

$\psi_{0.imp} := 0.7$ $\psi_S := 0.8$ $\psi_w := 0.3$ $\gamma_M := 1.25$

$$A_{bj} := \frac{(6.446)}{2} \cdot \frac{(6 + 6.2)}{2} \cdot m^2 = 19.66\,m^2$$

$\alpha_{A.edge} = 0.759$

$$g_{slab.2} := t_{slab.2} \cdot \rho_{concrete} \cdot g = 6.914 \cdot \frac{kN}{m^2}$$

$$N_{Ed.imp.2} := \left(1.35 \cdot g_{slab.2} + 1.5 \cdot q_{imp} \cdot \alpha_{A.edge} + 1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj} = 314.114 \cdot kN$$

$$N_{Ed.w.2} := \left(1.35 \cdot g_{slab.2} + 1.5 \cdot q_{imp} \cdot \psi_{0.imp} \cdot \alpha_{A.edge} + 1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w\right) \cdot A_{bj} = 300.628 \cdot kN$$

$$N_{Ed.s.2} := \left(1.35 \cdot g_{slab.2} + 1.5 \cdot q_{imp} \cdot \psi_{0.imp} \cdot \alpha_{A.edge} + 1.35 \cdot G_{eg} + 1.5 \cdot S_3 + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj} = 308.137 \cdot kN$$

check cross section class

$\varepsilon_2 := \sqrt{\frac{235MPa}{f_{yk}}} = 0.924$ $\quad$ $c := \frac{h_{sp.2} - 2 \cdot t_{sp.2}}{t_{sp.2}} = 16.75$ $\quad$ $\frac{c}{t} < 33\varepsilon$ $\quad$ TK 1

Cross section properties

$$A_{sp.2} := b_{sp.2} \cdot h_{sp.2} - \left(b_{sp.2} - 2 \cdot t_{sp.2}\right) \cdot \left(h_{sp.2} - 2 \cdot t_{sp.2}\right) = 3.744 \times 10^{-3} m^2$$

$$I_{y.2} := 2 \cdot \left[\left(b_{sp.2} - 2t_{sp.2}\right) \cdot t_{sp.2} \cdot \left(\frac{h_{sp.2} - t_{sp.2}}{2}\right)^2 + \frac{t_{sp.2} \cdot h_{sp.2}^{\ 3}}{12}\right] = 1.128 \times 10^7 \cdot mm^4$$

$$I_{z.2} := 2 \cdot \left[\left(h_{sp.2} - 2t_{sp.2}\right) \cdot t_{sp.2} \cdot \left(\frac{b_{sp.2} - t_{sp.2}}{2}\right)^2 + \frac{t_{sp.2} \cdot b_{sp.2}^{\ 3}}{12}\right] = 5.87 \times 10^{-6} m^4$$

$$I_{sp.2} := \min\left(I_{y.2}, I_{z.2}\right) = 5.87 \times 10^{-6}\, m^4$$

Buckling resistance of column

$$N_{cr.sp.2} := \frac{\pi^2 \cdot E \cdot I_{sp.2}}{L_p^{\,2}} = 1.084 \times 10^3 \cdot kN$$

$$\lambda_{sp.2} := \sqrt{\frac{A_{sp.2} \cdot f_{yk}}{N_{cr.sp.2}}} = 0.975$$

$$\alpha_{sp.2} := 0.21$$

$$\Phi_{sp.2} := 0.5 \cdot \left[1 + \alpha_{sp.2} \cdot \left(\lambda_{sp.2} - 0.2\right) + \lambda_{sp.2}^{\,2}\right] = 1.056$$

$$\chi_{sp.2} := \frac{1}{\Phi_{sp.2} + \sqrt{\Phi_{sp.2}^{\,2} - \lambda_{sp.2}^{\,2}}} = 0.683$$

$$N_{b.Rd.sp.2} := \chi_{sp.2} \cdot A_{sp.2} \cdot f_{yk} = 703.573 \cdot kN$$

$$\boxed{N_{sp.ut.2} := \frac{N_{Ed.imp.2}}{N_{b.Rd.sp.2}} = 44.646 \cdot \%}$$

$$c_{ez} := 1.54 \frac{kN}{m^2} \qquad q_b := 0.39$$

$$q_p := c_{ez} \cdot q_b = 0.601 \cdot \frac{kN}{m^2}$$

$c_{pe} := 0.7$ Cpe calculated for this specific case

$$q_w := q_p \cdot c_{pe} = 0.42 \cdot \frac{kN}{m^2}$$

$$q_{wh.m} := q_w \cdot 1.5 = 0.631 \cdot \frac{kN}{m^2} \qquad q_{wh.v} := 1.5 \cdot \psi_w \cdot q_w = 0.189 \cdot \frac{kN}{m^2}$$

$$M_{wh.m} := \frac{q_{wh.m} \cdot \frac{(6 + 6.2)}{2} m \cdot L_p^{\,2}}{8} = 5.396 \cdot kN \cdot m$$

$$M_{wh.v} := \frac{q_{wh.v} \cdot \frac{(6 + 6.2)}{2} m \cdot L_p^{\,2}}{8} = 1.619 \cdot kN \cdot m$$

Check interaction

$$W_{pl.sp.2} := \frac{I_{sp.2}}{\left(h_{sp.2} - 2t_{sp.2}\right) \cdot 0.5} = 8.761 \times 10^4 \cdot mm^3$$

$$M_{R.d.sp.2} := \chi_{sp.2} \cdot W_{pl.sp.2} \cdot f_{yk} = 16.464 \cdot kN \cdot m$$

$$\boxed{\frac{N_{Ed.w.2}}{N_{b.Rd.sp.2}} + \frac{M_{wh.m}}{M_{R.d.sp.2}} = 0.755}$$

wind main load

$$\boxed{\frac{N_{Ed.imp.2}}{N_{b.Rd.sp.2}} + \frac{M_{wh.v}}{M_{R.d.sp.2}} = 0.545}$$

imposed main load

Second order analysis

$$N_{Ed.2} := N_{Ed.w.2} = 300.628 \cdot kN$$

$$0.25 \cdot N_{b.Rd.sp.2} = 175.893 \cdot kN$$

Checking if interaction needs to be considered

$$e_{wind.2} := \frac{5 \cdot \left[q_{wh.m} \cdot \frac{(6 + 6.2) \cdot m}{2}\right] \cdot L_p^{\ 4}}{384 \cdot E \cdot I_{sp.2}} = 5.118 \cdot mm$$

$$e_{0d} := \frac{L_p}{250} = 13.4 \cdot mm$$

For buckling curve a and plastic analysis

$$N_{cr.sp.2} = 1.084 \times 10^3 \cdot kN$$

$$M_{II.2} := \frac{N_{Ed.2} \cdot \left(e_{0d} + e_{wind.2}\right)}{1 - \frac{N_{Ed.2}}{N_{cr.sp.2}}} = 7.703 \cdot kN \cdot m$$

$$M_{wind} := \frac{q_{wh.m} \cdot \frac{(6 + 6.2)}{2} m \cdot L_p^{\,2}}{8} = 5.396 \cdot kN \cdot m$$

$$M_{Ed.2} := M_{II.2} + M_{wind} = 13.099 \cdot kN \cdot m$$

$$M_{R.d.sp.2} = 16.464 \cdot kN \cdot m$$

$$n_2 := \frac{N_{Ed.2}}{N_{b.Rd.sp.2}} = 0.427$$

$$a_{p.2} := \frac{A_{sp.2} - 2 \cdot b_{sp.2} \cdot t_{sp.2}}{A_{sp.2}} = 0.573$$

$$a_{ps.2} := \left| \begin{array}{l} a_{p.2} \quad \text{if } a_{p.2} \le 0.5 \\ 0.5 \quad \text{otherwise} \end{array} \right.$$

$$\delta_{sp.2} := \frac{\left(1 - n_2\right)}{1 - \left(0.5 \cdot a_{ps.2}\right)} = 0.764$$

$$M_{N.R} := M_{R.d.sp.2} \cdot \delta_{sp.2} = 12.572 \cdot kN \cdot m$$

$$\boxed{M_{int.ut} := \frac{M_{Ed.2}}{M_{R.d.sp.2}} = 79.563 \cdot \%}$$

Steeel Columns VKR - Inner columns - Level 1

$b_{sp.2} := 100mm$ $h_{sp.2} := 150mm$ $t_{sp.2} := 8mm$

$f_{yk} := 235MPa$ $A_{bj.m} := \frac{(6.446 + 5.165)}{2} \cdot \frac{(6 + 6.2)}{2} \cdot m^2 = 35.414\,m^2$

$\alpha_{A.mid} = 0.641$

check cross section class

$\varepsilon_2 := \sqrt{\frac{235MPa}{f_{yk}}} = 1$ $c := \frac{h_{sp.2} - 2 \cdot t_{sp.2}}{t_{sp.2}} = 16.75$ $\frac{c}{t} < 33\varepsilon$

cross section properties

$$A_{sp.2} := b_{sp.2} \cdot h_{sp.2} - \left(b_{sp.2} - 2 \cdot t_{sp.2}\right) \cdot \left(h_{sp.2} - 2 \cdot t_{sp.2}\right) = 3.744 \times 10^{-3}\,m^2$$

$$I_{y.2} := 2 \cdot \left[\left(b_{sp.2} - 2t_{sp.2}\right) \cdot t_{sp.2} \cdot \left(\frac{h_{sp.2} - t_{sp.2}}{2}\right)^2 + \frac{t_{sp.2} \cdot h_{sp.2}^{\ 3}}{12}\right] = 1.128 \times 10^7 \cdot mm^4$$

$$I_{z.2} := 2 \cdot \left[\left(h_{sp.2} - 2t_{sp.2}\right) \cdot t_{sp.2} \cdot \left(\frac{b_{sp.2} - t_{sp.2}}{2}\right)^2 + \frac{t_{sp.2} \cdot b_{sp.2}^{\ 3}}{12}\right] = 5.87 \times 10^6 \cdot mm^4$$

$$I_{sp.2} := \min\left(I_{y.2}, I_{z.2}\right) = 5.87 \times 10^{-6}\,m^4$$

Buckling resistance of column

$$N_{cr.sp.2} := \frac{\pi^2 \cdot E \cdot I_{sp.2}}{L_p^2} = 1.084 \times 10^3 \cdot kN$$

$$\lambda_{sp.2} := \sqrt{\frac{A_{sp.2} \cdot f_{yk}}{N_{cr.sp.2}}} = 0.901$$

$$\alpha_{sp.2} := 0.21$$

$$\Phi_{sp.2} := 0.5 \cdot \left[1 + \alpha_{sp.2} \cdot \left(\lambda_{sp.2} - 0.2\right) + \lambda_{sp.2}^2\right] = 0.979$$

$$\chi_{sp.2} := \frac{1}{\Phi_{sp.2} + \sqrt{\Phi_{sp.2}^2 - \lambda_{sp.2}^2}} = 0.733$$

$$N_{b.Rd.sp.2} := \chi_{sp.2} \cdot A_{sp.2} \cdot f_{yk} = 645.241 \cdot kN$$

$$N_{Ed.imp.2} := \left(1.35 \cdot g_{slab.2} + 1.5 \cdot q_{imp} \cdot \alpha_{A.mid} + 1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj.m} = 547.089 \cdot kN$$

$$N_{Ed.w.2} := \left(1.35 \cdot g_{slab.2} + 1.5 \cdot q_{imp} \cdot \psi_{0.imp} \cdot \alpha_{A.mid} + 1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w\right) \cdot A_{bj.m} = 528.412 \cdot kN$$

$$N_{Ed.s.2} := \left(1.35 \cdot g_{slab.2} + 1.5 \cdot q_{imp} \cdot \psi_{0.imp} \cdot \alpha_{A.mid} + 1.35 \cdot G_{eg} + 1.5 \cdot S_3 + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj.m} = 541.936 \cdot kN$$

$$\boxed{N_{sp.ut.2} := \frac{N_{Ed.imp.2}}{N_{b.Rd.sp.2}} = 84.788 \cdot \%}$$

Steeel Columns VKR - Outer columns, mid wall - Level 2

$b_{sp.2} := 80mm$ $h_{sp.2} := 80mm$ $t_{sp.2} := 7.1mm$ $f_{yk} := 275MPa$ $L_p := 3.35m$

Dimensions are checked and are according
to SSAB's assortment.

$S_3 := 3 \cdot 0.8 \frac{kN}{m^2}$ $Q_w := 0.322 \frac{kN}{m^2}$ $G_{eg} := 0.152 \frac{kN}{m^2}$ $E := 210GPa$

$\psi_{0.imp} := 0.7$ $\psi_S := 0.8$ $\psi_w := 0.3$ $\psi_M := 1.25$

$$A_{bj} := \frac{(6.446)}{2} \cdot \frac{(6 + 6.2)}{2} \cdot m^2 = 19.66\,m^2$$

$$g_{slab.2} := t_{slab.2} \cdot \rho_{concrete} \cdot g = 6.914 \cdot \frac{kN}{m^2}$$

$$N_{Ed.imp.2} := \left(1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj} = 63.505 \cdot kN$$

$$N_{Ed.w.2} := \left(1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w\right) \cdot A_{bj} = 70.152 \cdot kN$$

$$N_{Ed.s.2} := \left(1.35 \cdot G_{eg} + 1.5 \cdot S_3 + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj} = 77.66 \cdot kN$$

check cross section class

$\varepsilon_2 := \sqrt{\frac{235MPa}{f_{yk}}} = 0.924$ $c := \frac{h_{sp.2} - 2 \cdot t_{sp.2}}{t_{sp.2}} = 9.268$ $\frac{c}{t} < 33\varepsilon$ TK 1

cross section properties

$$A_{sp.2} := b_{sp.2} \cdot h_{sp.2} - \left(b_{sp.2} - 2 \cdot t_{sp.2}\right) \cdot \left(h_{sp.2} - 2 \cdot t_{sp.2}\right) = 2.07 \times 10^{-3}\,m^2$$

$$I_{y.2} := 2 \cdot \left[\left(b_{sp.2} - 2t_{sp.2}\right) \cdot t_{sp.2} \cdot \left(\frac{h_{sp.2} - t_{sp.2}}{2}\right)^2 + \frac{t_{sp.2} \cdot h_{sp.2}^{\ 3}}{12} \right] = 1.847 \times 10^6 \cdot mm^4$$

$$I_{z.2} := 2 \cdot \left[\left(h_{sp.2} - 2t_{sp.2}\right) \cdot t_{sp.2} \cdot \left(\frac{b_{sp.2} - t_{sp.2}}{2}\right)^2 + \frac{t_{sp.2} \cdot b_{sp.2}^{\ 3}}{12} \right] = 1.847 \times 10^{-6} m^4$$

$$I_{sp.2} := \min\left(I_{y.2}, I_{z.2}\right) = 1.847 \times 10^{-6} m^4$$

Buckling resistance of column

$$N_{cr.sp.2} := \frac{\pi^2 \cdot E \cdot I_{sp.2}}{L_p^{\ 2}} = 341.159 \cdot kN$$

$$\lambda_{sp.2} := \sqrt{\frac{A_{sp.2} \cdot f_{yk}}{N_{cr.sp.2}}} = 1.292$$

$$\alpha_{sp.2} := 0.21$$

$$\Phi_{sp.2} := 0.5 \cdot \left[1 + \alpha_{sp.2} \cdot \left(\lambda_{sp.2} - 0.2\right) + \lambda_{sp.2}^{\ 2}\right] = 1.449$$

$$\chi_{sp.2} := \frac{1}{\Phi_{sp.2} + \sqrt{\Phi_{sp.2}^{\ 2} - \lambda_{sp.2}^{\ 2}}} = 0.475$$

$$N_{b.Rd.sp.2} := \chi_{sp.2} \cdot A_{sp.2} \cdot f_{yk} = 270.404 \cdot kN$$

$$N_{sp.ut.2} := \frac{N_{Ed.s.2}}{N_{b.Rd.sp.2}} = 28.72 \cdot \%$$

$c_{ez} := 1.54 \frac{kN}{m^2}$ $\quad q_b := 0.39$ $\quad q_p := c_{ez} \cdot q_b = 0.601 \cdot \frac{kN}{m^2}$ $\quad c_{pe} := 0.7$

$$q_w := q_p \cdot c_{pe} = 0.42 \cdot \frac{kN}{m^2}$$

$q_{wh.m} := q_w \cdot 1.5 = 0.631 \cdot \frac{kN}{m^2}$ $\quad q_{wh.v} := 1.5 \cdot \psi_w \cdot q_w = 0.189 \cdot \frac{kN}{m^2}$

$$M_{wh.m} := \frac{q_{wh.m} \cdot \frac{(6 + 6.2)}{2} m \cdot L_p^{\,2}}{8} = 5.396 \cdot kN \cdot m$$

$$M_{wh.v} := \frac{q_{wh.v} \cdot \frac{(6 + 6.2)}{2} m \cdot L_p^{\,2}}{8} = 1.619 \cdot kN \cdot m$$

Check interaction

$$W_{pl.sp.2} := \frac{I_{sp.2}}{\left(h_{sp.2} - 2t_{sp.2}\right) \cdot 0.5} = 5.615 \times 10^4 \cdot mm^3$$

$$M_{R.d.sp.2} := \chi_{sp.2} \cdot W_{pl.sp.2} \cdot f_{yk} = 7.333 \cdot kN \cdot m$$

$\frac{N_{Ed.w.2}}{N_{b.Rd.sp.2}} + \frac{M_{wh.m}}{M_{R.d.sp.2}} = 99.531 \cdot \%$ $\quad$ wind main load

$$\frac{N_{Ed.imp.2}}{N_{b.Rd.sp.2}} + \frac{M_{wh.v}}{M_{R.d.sp.2}} = 45.561 \cdot \%$$

imposed main load

Steeel Columns VKR - Inner columns - Level 2

$b_{sp.2} := 80mm$ $\quad h_{sp.2} := 80mm$ $\quad t_{sp.2} := 7.1mm$

$f_{yk} := 235MPa$ $\quad A_{bi.m} := \frac{(6.446 + 5.165)}{2} \cdot \frac{(6 + 6.2)}{2} \cdot m^2 = 35.414\,m^2$

check cross section class

$\varepsilon_2 := \sqrt{\frac{235MPa}{f_{yk}}} = 1$ $\quad c := \frac{h_{sp.2} - 2 \cdot t_{sp.2}}{t_{sp.2}} = 9.268$ $\quad \frac{c}{t} < 33\varepsilon$

cross section properties

$$A_{sp.2} := b_{sp.2} \cdot h_{sp.2} - \left(b_{sp.2} - 2 \cdot t_{sp.2}\right) \cdot \left(h_{sp.2} - 2 \cdot t_{sp.2}\right) = 2.07 \times 10^{-3}\,m^2$$

$$I_{y.2} := 2 \cdot \left[\left(b_{sp.2} - 2t_{sp.2}\right) \cdot t_{sp.2} \cdot \left(\frac{h_{sp.2} - t_{sp.2}}{2}\right)^2 + \frac{t_{sp.2} \cdot h_{sp.2}^{\,3}}{12}\right] = 1.847 \times 10^6 \cdot mm^4$$

$$I_{z.2} := 2 \cdot \left[\left(h_{sp.2} - 2t_{sp.2}\right) \cdot t_{sp.2} \cdot \left(\frac{b_{sp.2} - t_{sp.2}}{2}\right)^2 + \frac{t_{sp.2} \cdot b_{sp.2}^{\,3}}{12}\right] = 1.847 \times 10^6 \cdot mm^4$$

$$I_{sp.2} := \min\left(I_{y.2}, I_{z.2}\right) = 1.847 \times 10^{-6}\,m^4$$

Buckling resistance of column

$$N_{cr.sp.2} := \frac{\pi^2 \cdot E \cdot I_{sp.2}}{L_p^{\,2}} = 341.159 \cdot kN$$

$$\lambda_{sp.2} := \sqrt{\frac{A_{sp.2} \cdot f_{yk}}{N_{cr.sp.2}}} = 1.194$$

$$\alpha_{sp.2} := 0.21$$

$$\Phi_{sp.2} := 0.5 \cdot \left[1 + \alpha_{sp.2} \cdot \left(\lambda_{sp.2} - 0.2\right) + \lambda_{sp.2}^{\;2}\right] = 1.317$$

$$\chi_{sp.2} := \frac{1}{\Phi_{sp.2} + \sqrt{\Phi_{sp.2}^{\;2} - \lambda_{sp.2}^{\;2}}} = 0.534$$

$$N_{b.Rd.sp.2} := \chi_{sp.2} \cdot A_{sp.2} \cdot f_{yk} = 259.647 \cdot kN$$

$$N_{Ed.w.2} := \left(1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w\right) \cdot A_{bj.m} = 126.363 \cdot kN$$

$$N_{Ed.s.2} := \left(1.35 \cdot G_{eg} + 1.5 \cdot S_3 + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj.m} = 139.887 \cdot kN$$

$$\boxed{N_{sp.ut.2} := \frac{N_{Ed.s.2}}{N_{b.Rd.sp.2}} = 53.876 \cdot \%}$$

Columns

A.2 System 3. Calculations

SYSTEM 3 - Steel column and beam system with CLT slabs

Slab

Beams

Hat-beams HSQ - Mid beams

$L_h := 6m$ $\quad b_h := (6.646 + 5.165) \cdot m = 11.811\,m$

$f_{yd} := 235MPa$ $\quad \varepsilon := \sqrt{\frac{235MPa}{f_{yd}}} = 1$ $\quad S_3 := 3 \cdot 0.8 \frac{kN}{m^2}$

$t_{öf} := 30mm$ $\quad b_{öf} := 100mm$ $\quad t_w := 8mm$ $\quad h_w := 160mm$

$t_{uf} := 20mm$ $\quad b_{uf} := 300mm$ $\quad a := 4mm$

$f_{fb} := \frac{b_{uf}}{2} - \frac{b_{öf}}{2} - t_w - a = 88 \cdot mm$ $\quad \rho_{steel} := 7800 \frac{kg}{m^3}$

$\frac{b_{öf}}{t_{öf}} = 3.333$ < 38ε för cross section class 2

$\frac{f_{fb}}{t_{uf}} = 4.4$ < 10ε för cross section class 2

$$y_{tp} := \frac{t_{öf} \cdot b_{öf} \cdot \left(\frac{t_{öf}}{2}\right) + 2 \cdot t_w \cdot h_w \cdot \left(7mm + \frac{h_w}{2}\right) + t_{uf} \cdot b_{uf} \cdot \left(7mm + h_w + \frac{t_{uf}}{2}\right)}{t_{öf} \cdot b_{öf} + 2 \cdot t_w \cdot h_w + t_{uf} \cdot b_{uf}} = 115.028 \cdot mm$$

$$W_{pl} := b_{öf} \cdot t_{öf} \cdot \left(y_{tp} - \frac{t_{öf}}{2}\right) + 2 \cdot h_w \cdot t_w \cdot \left[y_{tp} - \left(7mm + \frac{h_w}{2}\right)\right] \ldots = 7.437 \times 10^5 \cdot mm^3$$
$$+ b_{uf} \cdot t_{uf} \cdot \left(7mm + h_w + \frac{t_{uf}}{2} - y_{tp}\right)$$

$M_{pl.Rd} := W_{pl} \cdot f_{yd} = 174.762 \cdot kN \cdot m$

$b_h = 11.811\,m$ $\quad L_h = 6\,m$

$A_{golv.m} := b_h \cdot L_h = 70.866\,m^2$ $\quad \alpha_{A.mid} := 0.5 + \dfrac{10m^2}{A_{golv.m}} = 0.641$

$\psi_{0.imp} := 0.7$ $\quad \psi_S := 0.8$ $\quad \psi_w := 0.3$

$g_{eg} = 1.257 \cdot \dfrac{kN}{m^2}$ $\quad G_{eg} := 0.152\dfrac{kN}{m^2}$ $\quad S_3 = 2.4 \cdot \dfrac{kN}{m^2}$ $\quad Q_w := 0.322\dfrac{kN}{m^2}$

$Q_k := \dfrac{q_{imp} \cdot b_h}{2} = 17.716 \cdot \dfrac{kN}{m}$ $\quad G_{slab} := g_{eg} \cdot \dfrac{b_h}{2} = 7.421 \cdot \dfrac{kN}{m}$

$$G_{s.balk} := \rho_{steel} \cdot g \cdot \left(t_{öf} \cdot b_{öf} + 2 \cdot t_w \cdot h_w + t_{uf} \cdot b_{uf}\right) = 0.884 \cdot \frac{kN}{m}$$

$$M_{max.balk} := \left[1.35 \cdot \left(G_{slab} + G_{s.balk}\right) \cdot 0.0772 + 1.5 \cdot Q_k \cdot \alpha_{A.mid} \cdot 0.0996\right] \cdot L_h^2 = 92.25 \cdot kN \cdot m$$

$$\boxed{M_{util} := \frac{M_{max.balk}}{M_{pl.Rd}} = 52.786 \cdot \%}$$

Shear force Capacity

$$V_{Rd.stålb} := \frac{2 \cdot t_w \cdot h_w \cdot f_{yd}}{\sqrt{3}} = 347.334 \cdot kN$$

$$V_{max.stålb} := 1.35 \cdot \left(G_{slab} + G_{s.balk}\right) \cdot (0.6071 + 0.5357) \cdot L_h + 1.5 \cdot Q_k \cdot \alpha_{A.mid} \cdot (0.6205 + 0.6026)L_h = 201.909 \cdot kN$$

$\eta := 1.2$ $\quad$ Dependent on steel class

$$\boxed{\begin{array}{ll} \text{"Need for further checks"} & \text{if } \dfrac{h_w}{t_w} \geq 75 \cdot \dfrac{\varepsilon}{\eta} \\ \text{"No need for further checks"} & \text{otherwise} \end{array} = \text{"No need for further checks"}}$$

$$V_{uti.sbalk} := \frac{\frac{V_{max.stålb}}{2}}{V_{Rd.stålb}} = 29.066 \cdot \%$$

Deflection

$L_h = 6\,m$ Calculating for the worst case with three spans of 6 meters

$t_{öf} := 30mm$ $b_{öf} := 100mm$ $t_w := 8mm$ $h_w := 160mm$ $\psi_2 := 0.6$

$t_{uf} := 20mm$ $b_{uf} := 300mm$ $a := 4mm$ $E_{steel} := 210GPa$

$h_{tot} := t_{uf} + h_w + 7mm = 187 \cdot mm$ $y_{tp} = 0.115\,m$

$$I_{tot.2} := \frac{b_{uf} \cdot t_{uf}^3}{12} + b_{uf} \cdot t_{uf} \cdot \left(h_{tot} - y_{tp} - \frac{t_{uf}}{2}\right)^2 \ldots + 2\left[\frac{t_w \cdot h_w^3}{12} + t_w \cdot h_w \cdot \left(t_{öf} + \frac{h_w}{2} - y_{tp}\right)^2\right] + \frac{b_{öf} \cdot t_{öf}^3}{12} \ldots + b_{öf} \cdot t_{öf} \cdot \left(y_{tp} - \frac{t_{öf}}{2}\right)^2 = 5.901 \times 10^{-5}\,m^4$$

$$Q_{sls.perm} := \left(G_{s.balk} + G_{slab}\right) = 8.305 \cdot \frac{kN}{m}$$

$$Q_{sls.var} := Q_k = 17.716 \cdot \frac{kN}{m}$$

$\frac{L_h}{300} = 20 \cdot mm$ requirement for permanent load $\frac{L_h}{250} = 24 \cdot mm$

$\frac{L_h}{400} = 15 \cdot mm$ requirement for variable load

$$v_{perm} := \frac{0.99 \cdot Q_{sls.perm} \cdot L_h^4}{100 \cdot E_{steel} \cdot I_{tot.2}} = 8.599 \cdot mm$$

$$v_{var} := \frac{0.99 \cdot Q_{sls.var} \cdot L_h^4}{100 \cdot E_{steel} \cdot I_{tot.2}} = 18.343 \cdot mm$$

$$v_{tot} := v_{perm} + v_{var} \cdot \psi_2 = 19.605 \cdot mm$$

$$\boxed{\delta_{util.perm} := \frac{v_{perm}}{\frac{L_h}{300}} = 42.994 \cdot \%}$$

$$\boxed{\delta_{util.var} := \frac{v_{var} \cdot \psi_2}{\frac{L_h}{400}} = 73.371 \cdot \%}$$

$$\boxed{\delta_{util.tot} := \frac{v_{tot}}{\frac{L_h}{300}} = 98.023 \cdot \%}$$

One sided HSQ - beam Edge beam

$L_h := 6m$ $\quad b_h := (6.646 + 5.165) \cdot m = 11.811\,m$

$f_{yd} := 235MPa$ $\quad \varepsilon := \sqrt{\frac{235MPa}{f_{yd}}} = 1$ $\quad S_3 := 3 \cdot 0.8 \frac{kN}{m^2}$

$t_{öf} := 30mm$ $\quad b_{öf} := 69mm$ $\quad t_w := 8mm$ $\quad h_w := 150mm$

$t_{uf} := 20mm$ $\quad b_{uf} := 175mm$ $\quad a := 4mm$

$f_{fb} := \frac{b_{uf}}{2} - \frac{b_{öf}}{2} - t_w - a = 41 \cdot mm$ $\quad \rho_{steel} := 7800 \frac{kg}{m^3}$

$\frac{b_{öf}}{t_{öf}} = 2.3$ < 38ε for cross section class 2

$\frac{f_{fb}}{t_{uf}} = 2.05$ < 10ε for cross section class 2

$$y_{tp} := \frac{t_{öf} \cdot b_{öf} \cdot \left(\frac{t_{öf}}{2}\right) + 2 \cdot t_w \cdot h_w \cdot \left(7mm + \frac{h_w}{2}\right) + t_{uf} \cdot b_{uf} \cdot \left(7mm + h_w + \frac{t_{uf}}{2}\right)}{t_{öf} \cdot b_{öf} + 2 \cdot t_w \cdot h_w + t_{uf} \cdot b_{uf}} = 101.926 \cdot mm$$

$$W_{pl} := b_{öf} \cdot t_{öf} \cdot \left(y_{tp} - \frac{t_{öf}}{2}\right) + 2 \cdot h_w \cdot t_w \cdot \left[y_{tp} - \left(7mm + \frac{h_w}{2}\right)\right] \dots = 4.555 \times 10^5 \cdot mm^3$$
$$+ b_{uf} \cdot t_{uf} \cdot \left(7mm + h_w + \frac{t_{uf}}{2} - y_{tp}\right)$$

$$M_{pl.Rd} := W_{pl} \cdot f_{yd} = 107.047 \cdot kN \cdot m$$

$b_h = 11.811\,m$ $\quad$ $L_h = 6\,m$

$A_{golv.m} := (6.446m) \cdot L_h = 38.676\,m^2$ $\quad$ $\alpha_{A.edge} := 0.5 + \frac{10m^2}{A_{golv.m}} = 0.759$

$\psi_{0.imp} := 0.7$ $\quad$ $\psi_S := 0.8$ $\quad$ $\psi_w := 0.3$

$g_{eg} = 1.257 \cdot \frac{kN}{m^2}$ $\quad$ $G_{eg} := 0.152 \frac{kN}{m^2}$ $\quad$ $S_3 = 2.4 \cdot \frac{kN}{m^2}$ $\quad$ $Q_w := 0.322 \frac{kN}{m^2}$

$Q_k := q_{imp} \cdot \frac{(6.446m)}{2} = 9.669 \cdot \frac{kN}{m}$ $\quad$ $G_{slab} := g_{eg} \cdot \frac{(6.446m)}{2} = 4.05 \cdot \frac{kN}{m}$

$$G_{s.balk} := \rho_{steel} \cdot g \cdot \left(t_{öf} \cdot b_{öf} + 2 \cdot t_w \cdot h_w + t_{uf} \cdot b_{uf}\right) = 0.61 \cdot \frac{kN}{m}$$

$$M_{max.balk} := \left[1.35 \cdot \left(G_{slab} + G_{s.balk}\right) \cdot 0.0772 + 1.5 \cdot Q_k \cdot \alpha_{A.edge} \cdot 0.0996\right] \cdot L_h^2 = 56.931 \cdot kN \cdot m$$

$$\boxed{M_{util} := \frac{M_{max.balk}}{M_{pl.Rd}} = 53.183 \cdot \%}$$

Torsional capacity

$$x_{tp} := \frac{t_{öf} \cdot b_{öf} \cdot \left(\frac{b_{öf}}{2} + t_w\right) + t_w \cdot h_w \cdot \left(\frac{t_w}{2}\right) + t_{uf} \cdot b_{uf} \cdot \left(\frac{b_{uf}}{2}\right) + t_w \cdot h_w \cdot \left(t_w + b_{öf} + \frac{t_w}{2}\right)}{t_{öf} \cdot b_{öf} + 2 \cdot t_w \cdot h_w + t_{uf} \cdot b_{uf}} = 0.062\,m$$

$$e_x := \frac{b_{uf} - \left(b_{öf} + t_w \cdot 2\right)}{2} + \left(b_{öf} + t_w \cdot 2\right) - x_{tp} = 0.068\,m$$

$$Q_{edgeb} := 1.35 \cdot \left(G_{slab} + G_{s.balk}\right) + 1.5 \cdot Q_k \cdot \alpha_{A.edge} = 17.292 \cdot \frac{kN}{m}$$

$$Q_{ecc} := Q_{edgeb} \cdot e_x = 1.171 \cdot \frac{kN \cdot m}{m}$$

$$T_{ed} := \frac{Q_{ecc} \cdot \left(L_h\right)}{2} = 3.514 \cdot kN \cdot m$$

$$A_{med} := \left(b_{öf} + t_w\right) \cdot \left(h_w + \frac{t_{uf}}{2} + 7mm - \frac{t_{öf}}{2}\right) = 0.012\,m^2$$

$$W_T := 2 \cdot A_{med} \cdot t_w = 1.873 \times 10^{-4}\,m^3$$

$$T_{Rd} := \frac{f_{yd} \cdot W_T}{\sqrt{3}} = 25.407 \cdot kN \cdot m$$

$$\boxed{T_{uti} := \frac{T_{ed}}{T_{Rd}} = 13.831 \cdot \%}$$

Shear force capacity

$$V_{Rd.stålb} := \frac{2 \cdot t_w \cdot h_w \cdot f_{yd}}{\sqrt{3}} = 325.626 \cdot kN$$

$$V_{pl.T.Rd} := V_{Rd.stålb} \cdot \left(1 - \frac{T_{ed}}{\frac{f_{yd} \cdot m^3}{\sqrt{3}}}\right) = 325.617 \cdot kN$$

Reduction due to torsion and shear interaction

$$V_{max.stålb} := \frac{1.35 \cdot (G_{slab} + G_{s.balk}) \cdot (0.6071 + 0.5357) \cdot L_h + 1.5 \cdot Q_k \cdot \alpha_{A.edge} \cdot (0.6205 + 0.6026) L_h}{2} = 61.936 \cdot kN$$

$$V_{uti.sbalk} := \frac{V_{max.stålb}}{V_{pl.T.Rd}} = 19.021 \cdot \%$$

$$\begin{array}{ll} \text{"Need for further checks"} & \text{if } \frac{h_w}{t_w} \geq 75 \cdot \frac{\varepsilon}{\eta} \\ \text{"No need for further checks"} & \text{otherwise} \end{array} = \text{"No need for further checks"}$$

Deflection

$L_h = 6\,m$ Calculating for the worst case with three spans of 6 meters

$t_{öf} := 30mm$ $b_{öf} := 69mm$ $t_w := 8mm$ $h_w := 150mm$

$t_{uf} := 20mm$ $b_{uf} := 175mm$ $a := 4mm$ $E_{steel} := 210GPa$

$h_{tot} := t_{uf} + h_w + 7mm = 177 \cdot mm$ $y_{tp} = 0.102\,m$

$$I_{tot.2} := \frac{b_{uf} \cdot t_{uf}^3}{12} + b_{uf} \cdot t_{uf} \cdot \left(h_{tot} - y_{tp} - \frac{t_{uf}}{2}\right)^2 \ldots + 2\left[\frac{t_w \cdot h_w^3}{12} + t_w \cdot h_w \cdot \left(t_{öf} + \frac{h_w}{2} - y_{tp}\right)^2\right] + \frac{b_{öf} \cdot t_{öf}^3}{12} \ldots + b_{öf} \cdot t_{öf} \cdot \left(y_{tp} - \frac{t_{öf}}{2}\right)^2 = 3.526 \times 10^{-5}\,m^4$$

$$Q_{sls.perm} := (G_{s.balk} + G_{slab}) = 4.66 \cdot \frac{kN}{m}$$

$$Q_{sls.var} := Q_k = 9.669 \cdot \frac{kN}{m}$$

$\frac{L_h}{300} = 20 \cdot mm$ requirement for permanent load

$\frac{L_h}{400} = 15 \cdot mm$ requirement for variable load

$$v_{perm} := \frac{0.99 \cdot Q_{sls.perm} \cdot L_h^{\,4}}{100 \cdot E_{steel} \cdot I_{tot.2}} = 8.075 \cdot mm$$

$$v_{var} := \frac{0.99 \cdot Q_{sls.var} \cdot L_h^{\,4}}{100 \cdot E_{steel} \cdot I_{tot.2}} = 16.756 \cdot mm$$

$$v_{tot} := v_{perm} + v_{var} \cdot \psi_2 = 18.128 \cdot mm$$

$$\boxed{\delta_{util.perm} := \frac{v_{perm}}{\frac{L_h}{300}} = 40.375 \cdot \%}$$

$$\boxed{\delta_{util.var} := \frac{v_{var} \cdot \psi_2}{\frac{L_h}{400}} = 67.022 \cdot \%}$$

$$\boxed{\delta_{util.tot} := \frac{v_{tot}}{\frac{L_h}{300}} = 90.641 \cdot \%}$$

Beams

Columns

Steel columns.

$f_y := 235MPa$ $\quad b_{sp} := 100mm$ $\quad h_{sp} := 100mm$ $\quad t_{sp} := 6.3mm$

$L_p := 3.35m$

Mid column, outer wall Floor 1

$$A_{bj} := \frac{(6.446)}{2} \cdot \frac{(6 + 6.2)}{2} \cdot m^2 = 19.66\,m^2$$

$$g_{eg} = 1.257 \cdot \frac{kN}{m^2} \qquad \text{CLT} - \text{slab}$$

$$N_{ULS} := \left(1.35 \cdot g_{eg} + 1.5 \cdot q_{imp} \cdot \alpha_{A.edge} + 1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj} = 163.968 \cdot kN$$

$$N_{ULS.wm} := \left(1.35 \cdot g_{eg} + 1.5 \cdot q_{imp} \cdot \psi_{0.imp} \cdot \alpha_{A.edge} + 1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w\right) \cdot A_{bj} = 150.482 \cdot kN$$

$$N_{ULS.sm} := \left(1.35 \cdot g_{eg} + 1.5 \cdot q_{imp} \cdot \psi_{0.imp} \cdot \alpha_{A.edge} + 1.35 \cdot G_{eg} + 1.5 \cdot S_3 + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj} = 157.99 \cdot kN$$

Horizontal wind load

$c_{ez} := 1.54 \frac{kN}{m^2}$ $\quad q_b := 0.39$ $\quad q_p := c_{ez} \cdot q_b = 0.601 \cdot \frac{kN}{m^2}$ $\quad c_{pe} := 0.7$

$q_w := q_p \cdot c_{pe} = 0.42 \cdot \frac{kN}{m^2}$

$k_m := 0.7$ $\quad E := 210GPa$

$q_{wh.m} := q_w \cdot 1.5 = 0.631 \cdot \frac{kN}{m^2}$ $\quad q_{wh.v} := 1.5 \cdot \psi_w \cdot q_w = 0.189 \cdot \frac{kN}{m^2}$

$$M_{wh.m} := \frac{q_{wh.m} \cdot \frac{(6 + 6.2)}{2} m \cdot L_p^{\ 2}}{8} = 5.396 \cdot kN \cdot m$$

$$M_{wh.v} := \frac{q_{wh.v} \cdot \frac{(6 + 6.2)}{2} m \cdot L_p^{\ 2}}{8} = 1.619 \cdot kN \cdot m$$

Check cross section class

$\varepsilon := \sqrt{235 \frac{MPa}{f_y}} = 1$ $\quad c_t := \frac{b_{sp} - 2 \cdot t_{sp}}{t_{sp}} = 13.873$ $\quad \frac{c}{t} < 33\varepsilon$ $\quad$ Cross section 1

Cross section properties

$$A_{sp} := b_{sp} \cdot h_{sp} - (b_{sp} - 2t_{sp}) \cdot (h_{sp} - 2t_{sp}) = 2.361 \times 10^{-3} m^2$$

$$I_y := 2 \cdot \left[(b_{sp} - 2t_{sp}) \cdot t_{sp} \cdot \left(\frac{h_{sp} - t_{sp}}{2} \right)^2 + \frac{t_{sp} \cdot h_{sp}^{\ 3}}{12} \right] = 3.467 \times 10^6 \cdot mm^4$$

$$I_z := 2 \cdot \left[(h_{sp} - 2t_{sp}) \cdot t_{sp} \cdot \left(\frac{b_{sp} - t_{sp}}{2} \right)^2 + \frac{t_{sp} \cdot b_{sp}^{\ 3}}{12} \right] = 3.467 \times 10^{-6} m^4$$

$$I_{sp} := \min(I_y, I_z) = 3.467 \times 10^{-6}\,m^4$$

Buckling resistance of column

$$N_{cr.sp} := \frac{\pi^2 \cdot E \cdot I_{sp}}{L_p^{\,2}} = 640.325 \cdot kN$$

$$\lambda_{sp} := \sqrt{\frac{A_{sp} \cdot f_y}{N_{cr.sp}}} = 0.931$$

$$\alpha_{sp} := 0.21$$

$$\Phi_{sp} := 0.5 \cdot \left[1 + \alpha_{sp} \cdot (\lambda_{sp} - 0.2) + \lambda_{sp}^{\,2}\right] = 1.01$$

$$\chi_{sp} := \frac{1}{\Phi_{sp} + \sqrt{\Phi_{sp}^{\,2} - \lambda_{sp}^{\,2}}} = 0.713$$

$$N_{b.Rd.sp} := \chi_{sp} \cdot A_{sp} \cdot f_y = 395.803 \cdot kN$$

$$\boxed{N_{sp.ut} := \frac{N_{ULS}}{N_{b.Rd.sp}} = 41.427 \cdot \%}$$

Check interaction

$$W_{pl.sp} := \frac{I_{sp}}{(h_{sp} - 2 \cdot t_{sp}) \cdot 0.5} = 7.934 \times 10^4 \cdot mm^3$$

$$M_{R.d.sp} := \chi_{sp} \cdot W_{pl.sp} \cdot f_y = 13.299 \cdot kN \cdot m$$

$$\boxed{\frac{N_{ULS.wm}}{N_{b.Rd.sp}} + \frac{M_{wh.m}}{M_{R.d.sp}} = 78.596 \cdot \%}$$ wind main load

$$\frac{N_{ULS}}{N_{b.Rd.sp}} + \frac{M_{wh.v}}{M_{R.d.sp}} = 53.6 \cdot \%$$ imposed main load

Second order analysis

$$N_{Ed} := N_{ULS.wm} = 150.482 \cdot kN$$

$$0.25 \cdot N_{b.Rd.sp} = 98.951 \cdot kN$$ Checking if interaction needs to be considered

$$e_{wind} := \frac{5 \cdot \left[q_{wh.m} \cdot \frac{(6 + 6.2) \cdot m}{2} \right] \cdot L_p^{\,4}}{384 \cdot E \cdot I_{sp}} = 8.664 \cdot mm$$

$$e_{0d} := \frac{L_p}{250} = 13.4 \cdot mm$$ For buckling curve a and plastic analysis

$$N_{cr.sp} = 640.325 \cdot kN$$

$$M_{II} := \frac{N_{ULS} \cdot \left(e_{0d} + e_{wind}\right)}{1 - \frac{N_{ULS}}{N_{cr.sp}}} = 4.863 \cdot kN \cdot m$$

$$M_{wind} := \frac{q_{wh.m} \cdot \frac{(6 + 6.2)}{2} m \cdot L_p^{\,2}}{8} = 5.396 \cdot kN \cdot m$$

$$M_{Ed} := M_{II} + M_{wind} = 10.26 \cdot kN \cdot m$$

$$M_{R.d.sp} = 13.299 \cdot kN \cdot m$$

$$n := \frac{N_{Ed}}{N_{b.Rd.sp}} = 0.38$$

$$a_p := \frac{A_{sp} - 2 \cdot b_{sp} \cdot t_{sp}}{A_{sp}} = 0.466$$

$$a_{ps} := \begin{vmatrix} a_p & \text{if } a_p \le 0.5 \\ 0.5 & \text{otherwise} \end{vmatrix}$$

$$\delta_{sp} := \frac{(1 - n)}{1 - \left(0.5 \cdot a_{ps}\right)} = 0.808$$

$$M_{N.R} := M_{R.d.sp} \cdot \delta_{sp} = 10.75 \cdot kN \cdot m$$

$$\boxed{M_{int.ut} := \frac{M_{Ed}}{M_{R.d.sp}} = 77.144 \cdot \%}$$

Mid column, inside the preschool. Floor 1

$f_y := 235MPa$ $\quad b_{sp} := 80mm$ $\quad h_{sp} := 120mm$ $\quad t_{sp} := 6.3mm$

$$A_{bj.m} := \frac{(6.446 + 5.165)}{2} \cdot \frac{(6 + 6.2)}{2} \cdot m^2 = 35.414\,m^2$$

Check cross section class

$$\varepsilon := \sqrt{235 \frac{MPa}{f_y}} = 1 \qquad c := \frac{b_{sp} - 2 \cdot t_{sp}}{t_{sp}} = 10.698 \qquad \frac{c}{t} < 33\varepsilon$$

Cross section class 1

Cross section properties

$$A_{sp} := b_{sp} \cdot h_{sp} - \left(b_{sp} - 2t_{sp}\right) \cdot \left(h_{sp} - 2t_{sp}\right) = 2.361 \times 10^{-3}\,m^2$$

$$I_y := 2 \cdot \left[\left(b_{sp} - 2t_{sp}\right) \cdot t_{sp} \cdot \left(\frac{h_{sp} - t_{sp}}{2}\right)^2 + \frac{t_{sp} \cdot h_{sp}^{\ 3}}{12}\right] = 4.559 \times 10^6 \cdot mm^4$$

$$I_z := 2 \cdot \left[(h_{sp} - 2t_{sp}) \cdot t_{sp} \cdot \left(\frac{b_{sp} - t_{sp}}{2} \right)^2 + \frac{t_{sp} \cdot b_{sp}^{\ 3}}{12} \right] = 2.375 \times 10^6 \cdot mm^4$$

$$I_{sp} := \min(I_y, I_z) = 2.375 \times 10^{-6}\, m^4$$

Buckling resistance of column

$$N_{cr.sp} := \frac{\pi^2 \cdot E \cdot I_{sp}}{L_p^{\ 2}} = 438.661 \cdot kN$$

$$\lambda_{sp} := \sqrt{\frac{A_{sp} \cdot f_y}{N_{cr.sp}}} = 1.125$$

$$\alpha_{sp} := 0.21$$

$$\Phi_{sp} := 0.5 \cdot \left[1 + \alpha_{sp} \cdot (\lambda_{sp} - 0.2) + \lambda_{sp}^{\ 2} \right] = 1.23$$

$$\chi_{sp} := \frac{1}{\Phi_{sp} + \sqrt{\Phi_{sp}^{\ 2} - \lambda_{sp}^{\ 2}}} = 0.579$$

$$N_{b.Rd.sp} := \chi_{sp} \cdot A_{sp} \cdot f_y = 321.404 \cdot kN$$

$$N_{ULS} := (1.35 \cdot g_{eg} + 1.5 \cdot q_{imp} \cdot \alpha_{A.mid} + 1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w \cdot \psi_w) \cdot A_{bj.m} = 276.634 \cdot kN$$

$$N_{ULS.wm} := (1.35 \cdot g_{eg} + 1.5 \cdot q_{imp} \cdot \alpha_{A.mid} \cdot \psi_{0.imp} + 1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w) \cdot A_{bj.m} = 257.957 \cdot kN$$

$$\boxed{N_{sp.ut.m} := \frac{N_{ULS}}{N_{b.Rd.sp}} = 86.071 \cdot \%}$$

Mid column, outer wall. Floor 2

Steel columns.

$f_y := 235\text{MPa}$ $\quad b_{sp} := 90\text{mm}$ $\quad h_{sp} := 90\text{mm}$ $\quad t_{sp} := 6.3\text{mm}$

$L_p := 3.35 \cdot m$

$$A_{bj} := \frac{(6.446)}{2} \cdot \frac{(6 + 6.2)}{2} \cdot m^2 = 19.66\,m^2$$

$$N_{ULS} := \left(1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj} = 63.505 \cdot kN$$

$$N_{ULS.wm} := \left(1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w\right) \cdot A_{bj} = 70.152 \cdot kN$$

$$N_{ULS.sm} := \left(1.35 \cdot G_{eg} + 1.5 \cdot S_3 + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj} = 77.66 \cdot kN$$

Horisontell vindlast

$c_{ez} := 1.54 \frac{kN}{m^2}$ $\quad q_b := 0.39$ $\quad q_p := c_{ez} \cdot q_b = 0.601 \cdot \frac{kN}{m^2}$ $\quad c_{pe} := 0.7$

$q_w := q_p \cdot c_{pe} = 0.42 \cdot \frac{kN}{m^2}$

$k_m := 0.7$ $\quad E := 210\text{GPa}$

$q_{wh.m} := q_w \cdot 1.5 = 0.631 \cdot \frac{kN}{m^2}$ $\quad q_{wh.v} := 1.5 \cdot \psi_w \cdot q_w = 0.189 \cdot \frac{kN}{m^2}$

$$M_{wh.m} := \frac{q_{wh.m} \cdot \frac{(6 + 6.2)}{2} m \cdot L_p^2}{8} = 5.396 \cdot kN \cdot m$$

$$M_{wh.v} := \frac{q_{wh.v} \cdot \frac{(6 + 6.2)}{2} m \cdot L_p^2}{8} = 1.619 \cdot kN \cdot m$$

Check cross section class

$\varepsilon := \sqrt{235\,\frac{\text{MPa}}{f_y}} = 1$ $\qquad$ $c_t := \frac{b_{sp} - 2 \cdot t_{sp}}{t_{sp}} = 12.286$ $\qquad$ $\frac{c}{t} < 33\varepsilon$ $\qquad$ Cross section 1

Cross section properties

$$A_{sp} := b_{sp} \cdot h_{sp} - \left(b_{sp} - 2t_{sp}\right) \cdot \left(h_{sp} - 2t_{sp}\right) = 2.109 \times 10^{-3}\,\text{m}^2$$

$$I_y := 2 \cdot \left[\left(b_{sp} - 2t_{sp}\right) \cdot t_{sp} \cdot \left(\frac{h_{sp} - t_{sp}}{2}\right)^2 + \frac{t_{sp} \cdot h_{sp}^{\ 3}}{12}\right] = 2.474 \times 10^6 \cdot \text{mm}^4$$

$$I_z := 2 \cdot \left[\left(h_{sp} - 2t_{sp}\right) \cdot t_{sp} \cdot \left(\frac{b_{sp} - t_{sp}}{2}\right)^2 + \frac{t_{sp} \cdot b_{sp}^{\ 3}}{12}\right] = 2.474 \times 10^{-6}\,\text{m}^4$$

$$I_{sp} := \min\left(I_y, I_z\right) = 2.474 \times 10^{-6}\,\text{m}^4$$

Buckling resistance of column

$$N_{cr.sp} := \frac{\pi^2 \cdot E \cdot I_{sp}}{L_p^{\ 2}} = 456.817 \cdot \text{kN}$$

$$\lambda_{sp} := \sqrt{\frac{A_{sp} \cdot f_y}{N_{cr.sp}}} = 1.042$$

$$\alpha_{sp} := 0.21$$

$$\Phi_{sp} := 0.5 \cdot \left[1 + \alpha_{sp} \cdot \left(\lambda_{sp} - 0.2\right) + \lambda_{sp}^{\ 2}\right] = 1.131$$

$$\chi_{sp} := \frac{1}{\Phi_{sp} + \sqrt{\Phi_{sp}^{\ 2} - \lambda_{sp}^{\ 2}}} = 0.636$$

$$N_{b.Rd.sp} := \chi_{sp} \cdot A_{sp} \cdot f_y = 315.468 \cdot \text{kN}$$

$$N_{sp.ut} := \frac{N_{ULS.sm}}{N_{b.Rd.sp}} = 24.617 \cdot \%$$

Check interaction

$$W_{pl.sp} := \frac{I_{sp}}{(h_{sp} - 2 \cdot t_{sp}) \cdot 0.5} = 6.391 \times 10^4 \cdot mm^3$$

$$M_{R.d.sp} := \chi_{sp} \cdot W_{pl.sp} \cdot f_y = 9.559 \cdot kN \cdot m$$

$$\frac{N_{ULS.wm}}{N_{b.Rd.sp}} + \frac{M_{wh.m}}{M_{R.d.sp}} = 78.688 \cdot \%$$

wind main load

$$\frac{N_{ULS}}{N_{b.Rd.sp}} + \frac{M_{wh.v}}{M_{R.d.sp}} = 37.066 \cdot \%$$

imposed main load

Mid column, inside the preschool. Floor 2

$f_y := 235MPa$ $\quad b_{sp} := 80mm$ $\quad h_{sp} := 80mm$ $\quad t_{sp} := 6.3mm$

$$A_{bj.m} := \frac{(6.446 + 5.165)}{2} \cdot \frac{(6 + 6.2)}{2} \cdot m^2 = 35.414\,m^2$$

$$N_{ULS} := (1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w \cdot \psi_w) \cdot A_{bj.m} = 107.122 \cdot kN$$

$$N_{ULS.wm} := (1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w) \cdot A_{bj.m} = 126.363 \cdot kN$$

$$N_{ULS.sm} := (1.35 \cdot G_{eg} + 1.5 \cdot S_3 + 1.5 \cdot Q_w \cdot \psi_w) \cdot A_{bj.m} = 139.887 \cdot kN$$

Check cross section class

$$\varepsilon := \sqrt{235 \frac{MPa}{f_y}} = 1 \qquad c := \frac{b_{sp} - 2 \cdot t_{sp}}{t_{sp}} = 10.698 \qquad \frac{c}{t} < 33\varepsilon$$

Cross section class 1

Cross section properties

$$A_{sp} := b_{sp} \cdot h_{sp} - \left(b_{sp} - 2t_{sp}\right) \cdot \left(h_{sp} - 2t_{sp}\right) = 1.857 \times 10^{-3}\, m^2$$

$$I_y := 2 \cdot \left[\left(b_{sp} - 2t_{sp}\right) \cdot t_{sp} \cdot \left(\frac{h_{sp} - t_{sp}}{2}\right)^2 + \frac{t_{sp} \cdot h_{sp}^{\ 3}}{12}\right] = 1.691 \times 10^6 \cdot mm^4$$

$$I_z := 2 \cdot \left[\left(h_{sp} - 2t_{sp}\right) \cdot t_{sp} \cdot \left(\frac{b_{sp} - t_{sp}}{2}\right)^2 + \frac{t_{sp} \cdot b_{sp}^{\ 3}}{12}\right] = 1.691 \times 10^6 \cdot mm^4$$

$$I_{sp} := \min\left(I_y, I_z\right) = 1.691 \times 10^{-6}\, m^4$$

Buckling resistance of column

$$N_{cr.sp} := \frac{\pi^2 \cdot E \cdot I_{sp}}{L_p^{\ 2}} = 312.264 \cdot kN$$

$$\lambda_{sp} := \sqrt{\frac{A_{sp} \cdot f_y}{N_{cr.sp}}} = 1.182$$

$$\alpha_{sp} := 0.21$$

$$\Phi_{sp} := 0.5 \cdot \left[1 + \alpha_{sp} \cdot \left(\lambda_{sp} - 0.2\right) + \lambda_{sp}^{\ 2}\right] = 1.302$$

$$\chi_{sp} := \frac{1}{\Phi_{sp} + \sqrt{\Phi_{sp}^{\ 2} - \lambda_{sp}^{\ 2}}} = 0.541$$

$$N_{b.Rd.sp} := \chi_{sp} \cdot A_{sp} \cdot f_y = 236.253 \cdot kN$$

$$N_{ULS} := \left(1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj.m} = 114.389 \cdot kN$$

$$N_{ULS.wm} := \left(1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w\right) \cdot A_{bj.m} = 126.363 \cdot kN$$

$$N_{ULS.s.} := \left(1.35 \cdot G_{eg} + 1.5 \cdot S_3 + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj.m} = 139.887 \cdot kN$$

$$\boxed{N_{sp.ut.m} := \frac{N_{ULS.s.}}{N_{b.Rd.sp}} = 59.211 \cdot \%}$$

Columns

A.3 System 4. Calculations

System 4: Glulam column and beam system with prefabricated glulam modules

Beams

Mid Beam - Level 1

$L_h := 6\text{m}$ $\quad b_h := (6.446 + 5.165) \cdot \text{m} = 11.611\,\text{m}$ $\quad h_b := 540\text{mm}$ $\quad b_b := 165\text{mm}$

$A_{golv.m} := b_h \cdot L_h = 69.666\,\text{m}^2$ $\quad \alpha_A := 0.5 + \dfrac{10\text{m}^2}{A_{golv.m}} = 0.644$

$\psi_{0.imp} := 0.7$ $\quad q_{imp} := 3\,\dfrac{\text{kN}}{\text{m}^2}$ $\quad \psi_S := 0.8$

$g_{slab} := 169\,\dfrac{\text{kg}}{\text{m}^2} \cdot g = 1.657 \cdot \dfrac{\text{kN}}{\text{m}^2}$ $\quad G_{eg} := 0.152\,\dfrac{\text{kN}}{\text{m}^2}$ $\quad S_3 := 3 \cdot 0.8\,\dfrac{\text{kN}}{\text{m}^2}$ $\quad Q_w := 0.322\,\dfrac{\text{kN}}{\text{m}^2}$

$Q_k := \dfrac{q_{imp} \cdot b_h}{2} = 17.416 \cdot \dfrac{\text{kN}}{\text{m}}$ $\quad G_{slab} := g_{slab} \cdot \dfrac{b_h}{2} = 9.622 \cdot \dfrac{\text{kN}}{\text{m}}$ $\quad \psi_w := 0.3$ $\quad \gamma_M := 1.25$

$G_{beam} := 430\,\dfrac{\text{kg}}{\text{m}^3} \cdot g \cdot h_b \cdot b_b = 0.376 \cdot \dfrac{\text{kN}}{\text{m}}$

$$M_{max.field} := \left[\left[1.35 \cdot \left(G_{slab} + G_{beam}\right)\right] \cdot 0.0703 + 1.5 \cdot Q_k \cdot \alpha_A \cdot 0.0957\right] \cdot L_h^2 = 92.079 \cdot \text{kN} \cdot \text{m}$$

$$M_{max.supp} := \left[\left[1.35 \cdot \left(G_{slab} + G_{beam}\right)\right] \cdot -0.125 + 1.5 \cdot Q_k \cdot \alpha_A \cdot -0.125\right] \cdot L_h^2 = -136.389 \cdot \text{kN} \cdot \text{m}$$

$$M_{max} := \max\left(M_{max.field}, -M_{max.supp}\right) = 136.389 \cdot \text{kN} \cdot \text{m}$$

$k_{mod} := 0.8$ $\quad k_h := \min\left[\left(\dfrac{600\text{mm}}{h_b}\right)^{0.1}, 1.1\right] = 1.011$

GL30c

$f_{m.k} := 30\text{MPa}$ $\quad f_{m.d} := k_h \cdot \dfrac{f_{m.k} \cdot k_{mod}}{\gamma_M} = 19.403 \cdot \text{MPa}$ $\quad E_{0.05} := 10800\text{MPa}$

$$W_b := \frac{b_b \cdot h_b^2}{6} = 8.019 \times 10^{-3} \cdot m^3$$

$$\sigma_{m.crit} := \frac{0.78 \cdot b_b^2 \cdot E_{0.05}}{h_b \cdot L_h \cdot 0.9} = 78.65 \cdot MPa$$

$$\lambda_{rel.m} := \sqrt{\frac{f_{m.k}}{\sigma_{m.crit}}} = 0.618$$

$$k_{cr} := \begin{cases} 1 \quad \text{if } \lambda_{rel.m} \le 0.75 \\ (1.56 - 0.75 \cdot \lambda_{rel.m}) \quad \text{if } 0.75 < \lambda_{rel.m} \le 1.4 \\ \dfrac{1}{\lambda_{rel.m}^2} \quad \text{if } \lambda_{rel.m} > 1.4 \end{cases}$$

$$k_{cr} = 1$$

$$M_{R.d} := f_{m.d} \cdot W_b \cdot k_{cr} = 155.596 \cdot kN \cdot m$$

$$\boxed{M_{uti} := \frac{M_{max}}{M_{R.d}} = 87.656 \cdot \%}$$

Shear force capacity

$$f_{v.k} := 3.5MPa$$

$$k_{cr.V} := \min\left(\frac{3.0MPa}{f_{v.k}}, 1\right) = 0.857$$

$$b_{ef} := k_{cr.V} b_b = 0.141\,m$$

$$A_{b.V} := h_b \cdot b_{ef} = 0.076\,m^2$$

$$f_{v.d} := \frac{f_{v.k} \cdot k_{mod}}{\gamma_M} = 2.24 \cdot MPa$$

$$V_{Rd} := \frac{A_{b.V} \cdot f_{v.d}}{1.5} = 114.048 \cdot kN$$

Maxumum shear force:

$$R_B := \left[1.35 \cdot \left(G_{slab} + G_{beam}\right)\right] \cdot (0.625 + 0.625) \cdot L_h + 1.5 \cdot Q_k \cdot \alpha_A \cdot (0.625 + 0.625)L_h = 227.316 \cdot kN$$

$$R_A := 0.375 \cdot \left[1.35 \cdot \left(G_{slab} + G_{beam}\right)\right] \cdot L_h + 0.375 \cdot \left(1.5 \cdot Q_k \cdot \alpha_A\right) \cdot L_h = 68.195 \cdot kN$$

$$V_{max} := -R_A + \left[1.5 \cdot Q_k \cdot \alpha_A + 1.35 \cdot \left(G_{slab} + G_{beam}\right)\right] \cdot L_h = 113.658 \cdot kN$$

$$\boxed{V_{ult} := \frac{V_{max}}{V_{Rd}} = 99.658 \cdot \%}$$

Deflection

Permanent

$\psi_2 := 0.6$

$h_b := 540mm$ $\quad$ $b_b := 165mm$ $\quad$ $E_{0.mean} := 13600MPa$ $\quad$ $k_{def} := 0.6$ $\quad$ $k_{mod} = 0.8$

$$E_{0.mean.final} := \frac{E_{0.mean}}{1 + k_{def}} = 8.5 \times 10^3 \cdot MPa$$

$$I_{beam} := \frac{b_b \cdot h_b^{\,3}}{12} = 2.165 \times 10^{-3} \, m^4$$

$$Q_{sls.perm} := G_{slab} + G_{beam} = 9.997 \cdot \frac{kN}{m}$$

$$v_{perm.inst} := \frac{0.912 \cdot Q_{sls.perm} \cdot L_h^{\,4}}{100 \cdot E_{0.mean} \cdot I_{beam}} = 4.013 \cdot mm$$

$$v_{final.perm} := v_{perm.inst} \cdot \left(1 + k_{def}\right) = 6.421 \cdot mm$$

Variable

$$Q_{sls.var} := Q_k = 17.416 \cdot \frac{kN}{m}$$

$$v_{var} := \frac{0.912 \cdot Q_{sls.var} \cdot L_h^{\,4}}{100 \cdot E_{0.mean} \cdot I_{beam}} = 6.991 \cdot mm$$

$$v_{final.var} := v_{var} \cdot \left(1 + k_{def} \cdot \psi_2\right) = 9.508 \cdot mm$$

Total Quasi

$$v_{final} := v_{final.var} + v_{final.perm} = 15.928 \cdot mm$$

$$\boxed{v_{final.uti} := \frac{v_{final}}{\frac{L_h}{300}} = 79.642 \cdot \%}$$

Frequent:

$$\psi_1 := 0.7$$

$$Q_{freq} := G_{slab} + G_{beam} + \left(Q_k \cdot \alpha_A\right) \cdot \psi_1 = 17.843 \cdot \frac{kN}{m}$$

$$v_{freq} := \frac{0.912 \cdot Q_{freq} \cdot L_h^{\,4}}{100 \cdot E_{0.mean} \cdot I_{beam}} = 7.162 \cdot mm$$

$$\boxed{v_{freq.uti} := \frac{v_{freq}}{\frac{L_h}{375}} = 44.764 \cdot \%}$$

Edge beams

$b_{h.k} := \frac{6.446}{2} \cdot m = 3.223\,m$ $\qquad b_{b.k} := 140mm$ $\qquad h_{b.k} := 450mm$

$A_{golv.k} := 2b_{h.k} \cdot L_h = 38.676\,m^2$ $\qquad \alpha_{A.k} := 0.5 + \frac{10m^2}{A_{golv.k}} = 0.759$

$$Q_{k.k} := q_{imp} \cdot b_{h.k} = 9.669 \cdot \frac{kN}{m}$$

$$G_{slab.k} := g_{slab} \cdot b_{h.k} = 5.342 \cdot \frac{kN}{m}$$

$$G_{beam.k} := 430 \frac{kg}{m^3} \cdot g \cdot h_{b.k} \cdot b_{b.k} = 0.266 \cdot \frac{kN}{m}$$

$$M_{max.field.k} := \left[\left[1.35 \cdot \left(G_{slab.k} + G_{beam.k}\right)\right] \cdot 0.0703 + 1.5 \cdot Q_{k.k} \cdot \alpha_{A.k} \cdot 0.0957\right] \cdot L_h^2 = 57.061 \cdot kN \cdot m$$

$$M_{max.supp.k} := \left[\left[1.35 \cdot \left(G_{slab.k} + G_{beam.k}\right)\right] \cdot -0.125 + 1.5 \cdot Q_{k.k} \cdot \alpha_{A.k} \cdot -0.125\right] \cdot L_h^2 = -83.572 \cdot kN \cdot m$$

$$M_{max.k} := \max\left(M_{max.field.k}, -M_{max.supp.k}\right) = 83.572 \cdot kN \cdot m$$

$f_{m.k} := 30MPa$ $\qquad k_{h.k} := \min\left[\left(\frac{600mm}{h_{b.k}}\right)^{0.1}, 1.1\right] = 1.029$ $\qquad$ GL30c

$$f_{m.d.k} := k_{h.k} \cdot \frac{f_{m.k} \cdot k_{mod}}{\gamma_M} = 19.76 \cdot MPa$$

$$W_{b.k} := \frac{b_{b.k} \cdot h_{b.k}^2}{6} = 4.725 \times 10^{-3} \cdot m^3$$

$$\sigma_{m.crit} := \frac{0.78 \cdot b_{b.k}^2 \cdot E_{0.05}}{h_{b.k} \cdot L_h \cdot 0.9} = 67.947 \cdot MPa$$

$$\lambda_{rel.m} := \sqrt{\frac{f_{m.k}}{\sigma_{m.crit}}} = 0.664$$

$$k_{cr} := \begin{vmatrix} 1 \ \text{ if } \ \lambda_{rel.m} \le 0.75 \\ (1.56 - 0.75 \cdot \lambda_{rel.m}) \ \text{ if } \ 0.75 < \lambda_{rel.m} \le 1.4 \\ \dfrac{1}{\lambda_{rel.m}^{\ 2}} \ \text{ if } \ \lambda_{rel.m} > 1.4 \end{vmatrix}$$

$k_{cr} = 1$

$M_{R.d.k} := f_{m.d.k} \cdot W_{b.k} = 93.368 \cdot kN \cdot m$

$$\boxed{M_{uti.k} := \frac{M_{max.k}}{M_{R.d.k}} = 89.508 \cdot \%}$$

Shear force capacity

$f_{v.k.k} := 3.5MPa$ $\qquad$ $k_{cr.k} := \min\left(\dfrac{3.0MPa}{f_{v.k.k}}, 1\right) = 0.857$

$b_{b.k} = 0.14\,m$ $\qquad$ $b_{ef.k} := k_{cr}\, b_{b.k} = 0.14\,m$

$A_{b.k} := h_{b.k} \cdot b_{ef.k} = 0.063\,m^2$

$$f_{v.d.k} := \frac{f_{v.k} \cdot k_{mod}}{\gamma_M}$$

$$V_{Rd.k} := \frac{A_{b.k} \cdot f_{v.d.k}}{1.5} = 94.08 \cdot kN$$

$R_{B.k} := \left[1.35 \cdot \left(G_{slab.k} + G_{beam.k}\right)\right] \cdot (0.625 + 0.625) \cdot L_h + 1.5 \cdot Q_{k.k} \cdot \alpha_{A.k} \cdot (0.625 + 0.625)L_h = 139.286 \cdot kN$

$R_{A.k} := 0.375 \cdot \left[1.35 \cdot \left(G_{slab.k} + G_{beam.k}\right)\right] \cdot L_h + 0.375 \cdot \left(1.5 \cdot Q_{k.k} \cdot \alpha_{A.k}\right) \cdot L_h = 41.786 \cdot kN$

$V_{max.k} := -R_{A.k} + \left[1.5 \cdot Q_{k.k} \cdot \alpha_{A.k} + 1.35 \cdot \left(G_{slab.k} + G_{beam.k}\right)\right] \cdot L_h = 69.643 \cdot kN$

$$\boxed{V_{ult.k} := \frac{V_{max.k}}{V_{Rd.k}} = 74.025 \cdot \%}$$

Deflection

Permanent

$\psi_2 := 0.6$

$b_{b.k} := 140mm$ $h_{b.k} := 450mm$ $E_{0.mean} := 13600MPa$ $k_{def} := 0.6$ $k_{mod} = 0.8$

$$E_{0.mean.final} := \frac{E_{0.mean}}{1 + k_{def}} = 8.5 \times 10^{3} \cdot MPa$$

$$I_{beam} := \frac{b_{b.k} \cdot h_{b.k}^{3}}{12} = 1.063 \times 10^{-3} m^{4}$$

$$Q_{sls.perm} := G_{slab.k} + G_{beam.k} = 5.607 \cdot \frac{kN}{m}$$

$$v_{perm.inst} := \frac{0.912 \cdot Q_{sls.perm} \cdot L_h^{4}}{100 \cdot E_{0.mean} \cdot I_{beam}} = 4.584 \cdot mm$$

$$v_{final.perm} := v_{perm.inst} \cdot \left(1 + k_{def}\right) = 7.334 \cdot mm$$

Variable

$$Q_{sls.var} := Q_{k.k} = 9.669 \cdot \frac{kN}{m}$$

$$v_{var} := \frac{0.912 \cdot Q_{sls.var} \cdot L_h^{4}}{100 \cdot E_{0.mean} \cdot I_{beam}} = 7.904 \cdot mm$$

$$v_{final.var} := v_{var} \cdot \left(1 + k_{def} \cdot \psi_2\right) = 10.75 \cdot mm$$

Total

$$v_{final} := v_{final.var} + v_{final.perm} = 18.084 \cdot mm$$

$$v_{final.uti} := \frac{v_{final}}{\frac{L_h}{300}} = 90.419 \cdot \%$$

Frequent:

$$\frac{L_h}{375} = 16 \cdot mm$$

$\psi_1 := 0.7$ For schools

$$Q_{freq} := G_{slab.k} + G_{beam.k} + \left(Q_{k.k} \cdot \alpha_{A.k}\right) \cdot \psi_1 = 10.741 \cdot \frac{kN}{m}$$

$$v_{freq} := \frac{0.912 \cdot Q_{freq} \cdot L_h^{\,4}}{100 \cdot E_{0.mean} \cdot I_{beam}} = 8.781 \cdot mm$$

$$v_{freq.uti} := \frac{v_{freq}}{\frac{L_h}{375}} = 54.88 \cdot \%$$

Mid beams between floor 2 and roof

$h_{b.2} := 495mm \qquad b_{b.2} := 140mm$

$G_{eg} := 0.152 \frac{kN}{m^2} \qquad S_3 := 3 \cdot 0.8 \frac{kN}{m^2} \qquad Q_w := 0.322 \frac{kN}{m^2}$

$\psi_w := 0.3 \qquad \psi_S := 0.8$

$$G_{beam.2} := 430 \frac{kg}{m^3} \cdot g \cdot h_{b.2} \cdot b_{b.2} = 0.292 \cdot \frac{kN}{m}$$

$$Q_{d.S} := 1.35 \cdot \frac{b_h}{2} \cdot G_{eg} + 1.5 \cdot S_3 \cdot \frac{b_h}{2} + 1.5 \cdot Q_w \cdot \frac{b_h}{2} \cdot \psi_w = 22.932 \cdot \frac{kN}{m}$$

$$Q_{d.w} := 1.35 \cdot \frac{b_h}{2} \cdot G_{eg} + 1.5 \cdot S_3 \cdot \frac{b_h}{2} \cdot \psi_S + 1.5 \cdot Q_w \cdot \frac{b_h}{2} = 20.715 \cdot \frac{kN}{m}$$

$$Q_{max} := \max\left(Q_{d.S}, Q_{d.w}\right) = 22.932 \cdot \frac{kN}{m}$$

$$M_{max.2} := Q_{max} \cdot 0.125 \cdot L_h^{\ 2} = 103.195 \cdot kN \cdot m$$

$$k_{h.2} := \min\left[\left(\frac{600mm}{h_{b.2}}\right)^{0.1}, 1.1\right] = 1.019$$

$$f_{m.d.2} := k_{h.2} \cdot \frac{f_{m.k} \cdot k_{mod}}{\gamma_M} = 19.573 \cdot MPa$$

$$W_{b.2} := \frac{b_{b.2} \cdot h_{b.2}^{\ 2}}{6} = 5.717 \times 10^{-3} \cdot m^3$$

$$M_{R.d.2} := f_{m.d.2} \cdot W_{b.2} = 111.903 \cdot kN \cdot m$$

$$\boxed{M_{uti.2} := \frac{M_{max.2}}{M_{R.d.2}} = 92.218 \cdot \%}$$

Shear force capacity

$f_{v.k} := 3.5MPa$ $\qquad$ $k_{cr} := \min\left(\frac{3.0MPa}{f_{v.k}}, 1\right) = 0.857$

$b_{b.2} = 0.14\,m$ $\qquad$ $b_{ef.2} := k_{cr}\, b_{b.2} = 0.12\,m$

$$A_{b.2} := h_{b.2} \cdot b_{ef.2} = 0.059\,m^2$$

$$f_{v.d.2} := \frac{f_{v.k} \cdot k_{mod}}{\gamma_M}$$

$$R_{B.2} := \left[1.35 \cdot \left(G_{eg} \cdot \frac{b_h}{2} + G_{beam.2}\right)\right] \cdot (0.625 + 0.625) \cdot L_h \ldots \quad = 168.838 \cdot kN$$
$$+ 1.5 \cdot \left(S_3 \cdot \frac{b_h}{2} \cdot \psi_S + 1.5 \cdot Q_w \cdot \frac{b_h}{2}\right) \cdot (0.625 + 0.625) L_h$$

$$R_{A.2} := 0.375 \cdot \left[1.35 \cdot \left(G_{eg} \cdot \frac{b_h}{2} + G_{beam.2}\right)\right] \cdot L_h + 0.375 \cdot 1.5 \cdot \left(S_3 \cdot \frac{b_h}{2} \cdot \psi_S + Q_w \cdot \frac{b_h}{2}\right) \cdot L_h = 47.497 \cdot kN$$

$$V_{max.2} := -R_{A.2} + \left[1.5 \cdot \left(S_3 \cdot \frac{b_h}{2} \cdot \psi_S + Q_w \cdot \frac{b_h}{2}\right) + 1.35 \cdot \left(G_{eg} \cdot \frac{b_h}{2} + G_{beam.2}\right)\right] \cdot L_h = 79.161 \cdot kN$$

$$V_{Rd.2} := \frac{A_{b.2} \cdot f_{v.d.2}}{1.5} = 88.704 \cdot kN$$

$$\boxed{V_{ult.2} := \frac{V_{max.2}}{V_{Rd.2}} = 89.242 \cdot \%}$$

Deflection

Permanent

$\psi_2 := 0.6$ $\psi_{2.s} := 0.2$ $\psi_{2.w} := 0$ $\psi_1 = 0.7$

$h_{b.2} = 495 \cdot mm$ $b_{b.2} := 140mm$ $E_{0.mean} := 13600MPa$ $k_{def} := 0.6$ $k_{mod} = 0.8$

$$E_{0.mean.final} := \frac{E_{0.mean}}{1 + k_{def}} = 8.5 \times 10^3 \cdot MPa$$

$$I_{beam} := \frac{b_{b.2} \cdot h_{b.2}^3}{12} = 1.415 \times 10^{-3} m^4$$

$$Q_{sls.perm} := G_{eg} \cdot \frac{b_h}{2} + S_3 \cdot \frac{b_h}{2} \cdot \psi_{2.s} + Q_w \cdot \frac{b_h}{2} \cdot \psi_{2.w} + G_{beam.2} = 3.961 \cdot \frac{kN}{m}$$

$$v_{perm.inst} := \frac{0.912 \cdot Q_{sls.perm} \cdot L_h^4}{100 \cdot E_{0.mean} \cdot I_{beam}} = 2.433 \cdot mm$$

$$v_{perm.creep} := \frac{0.912 \cdot Q_{sls.perm} \cdot L_h^4}{100 \cdot E_{0.mean.final} \cdot I_{beam}} = 3.893 \cdot mm$$

$$v_{final.perm} := v_{perm.inst} \cdot \left(1 + k_{def}\right) = 3.893 \cdot mm$$

$$\boxed{v_{final.uti} := \frac{v_{final.perm}}{\frac{L_h}{300}} = 19.464 \cdot \%}$$

Frequent:

$\psi_1 := 0.7$ $\psi_{1.s} := 0.6$ For schools

$$Q_{freq} := G_{eg} \cdot \frac{b_h}{2} + S_3 \cdot \frac{b_h}{2} \cdot \psi_{1.s} + Q_w \cdot \frac{b_h}{2} \cdot \psi_{2.w} + G_{beam.2} = 9.535 \cdot \frac{kN}{m}$$

$$v_{freq} := \frac{0.912 \cdot Q_{freq} \cdot L_h^{\ 4}}{100 \cdot E_{0.mean} \cdot I_{beam}} = 5.856 \cdot mm$$

$$\boxed{v_{freq.uti} := \frac{v_{freq}}{\frac{L_h}{375}} = 36.6 \cdot \%}$$

Beams

Columns

Columns

Mid column floor 1

$L_p := 3.125m$

$b_p := 160mm$ $h_p := 160mm$ $I_p := \frac{b_p \cdot h_p^{\ 3}}{12} = 5.461 \times 10^{-5}\, m^4$

$E_{0.05} := 11300MPa$ $\beta_c := 0.1$ $l_{ef} := L_p = 3.125\, m$

$f_{c.0k} := 24.5MPa$ $f_{c.0.d} := k_{mod} \cdot \frac{f_{c.0k}}{\gamma_M} = 15.68 \cdot MPa$

$f_{m.k.30} := 30MPa$ $f_{m.d.30} := k_{mod} \cdot k_h \cdot \frac{f_{m.k.30}}{\gamma_M} = 19.403 \cdot MPa$

$$N_{cr} := \frac{\pi^2 \cdot E_{0.05} \cdot I_p}{L_p^2} = 623.702 \cdot kN$$

Capacity of compression

$$i := \sqrt{\frac{I_p}{b_p \cdot h_p}} = 0.046\,m$$

$$\lambda := \frac{l_{ef}}{i} = 67.658$$

$$\lambda_{rel} := \frac{\lambda}{\pi} \cdot \sqrt{\frac{f_{c.0k}}{E_{0.05}}} = 1.003$$

$$\sigma_{crit} := \frac{0.78 \cdot b_p^2 \cdot E_{0.05}}{h_p \cdot L_p} = 4.513 \times 10^8 \cdot Pa$$

$$\lambda_{rel.m.p} := \sqrt{\frac{f_{m.k.30}}{\sigma_{crit}}} = 0.258$$

$$k := 0.5 \cdot \left[1 + \beta_c \cdot \left(\lambda_{rel} - 0.3\right) + \lambda_{rel}^2\right] = 1.038$$

$$k_c := \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^2}} = 0.766$$

$$N_{c.0.Rd} := f_{c.0.d} \cdot b_p \cdot h_p \cdot k_c = 307.416 \cdot kN$$

Loads

$$A_{bj} := \frac{(6.446)}{2} \cdot \frac{(6 + 6.2)}{2} \cdot m^2 = 19.66\,m^2$$

$$N_{ULS} := \left(1.35 \cdot g_{slab} + 1.5 \cdot q_{imp} \cdot \alpha_{A.k} + 1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj} = 174.603 \cdot kN$$

$$N_{ULS.wm} := \left(1.35 \cdot g_{slab} + 1.5 \cdot q_{imp} \cdot \alpha_{A.k} \cdot \psi_{0.imp} + 1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w\right) \cdot A_{bj} = 161.117 \cdot kN$$

$$N_{ULS.sm} := \left(1.35 \cdot g_{slab} + 1.5 \cdot q_{imp} \cdot \alpha_{A.k} \cdot \psi_{0.imp} + 1.35 \cdot G_{eg} + 1.5 \cdot S_3 + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj} = 168.625 \cdot kN$$

$$\boxed{\frac{N_{ULS}}{N_{c.0.Rd}} = 56.797 \cdot \%}$$

Horizontal wind load

$c_{ez} := 1.54 \frac{kN}{m^2}$ $\quad q_b := 0.39$ $\quad q_p := c_{ez} \cdot q_b = 0.601 \cdot \frac{kN}{m^2}$ $\quad c_{pe} := 0.7$

$$q_w := q_p \cdot c_{pe} = 0.42 \cdot \frac{kN}{m^2}$$

$$k_m := 0.7$$

$q_{wh.m} := q_w \cdot 1.5 = 0.631 \cdot \frac{kN}{m^2}$ $\quad q_{wh.v} := 1.5 \cdot \psi_w \cdot q_w = 0.189 \cdot \frac{kN}{m^2}$

$$M_{wh.m} := \frac{q_{wh.m} \cdot \frac{(6 + 6.2)}{2} m \cdot L_p^{\,2}}{8} = 4.696 \cdot kN \cdot m$$

$$M_{wh.v} := \frac{q_{wh.v} \cdot \frac{(6 + 6.2)}{2} m \cdot L_p^{\,2}}{8} = 1.409 \cdot kN \cdot m$$

$W_{ph} := \frac{h_p \cdot \left(b_p\right)^2}{6} = 6.827 \times 10^{-4} \cdot m^3$ In weak direction

$$k_{crit} := \begin{cases} 1 \ \text{ if } \lambda_{rel.m.p} \le 0.75 \\ \left(1.56 - 0.75 \cdot \lambda_{rel.m.p}\right) \ \text{ if } 0.75 < \lambda_{rel.m.p} \le 1.4 \\ \frac{1}{\lambda^2} \ \text{ otherwise} \end{cases} = 1$$

$$M_{Rd.p} := f_{m.d.30} \cdot W_{ph} \cdot k_{crit} = 13.246 \cdot kN \cdot m$$

$$\boxed{M_{uti.1} := \frac{M_{wh.m}}{M_{Rd.p}} = 35.451 \cdot \%}$$

$$\sigma_{ULS.h.wm} := \frac{M_{wh.m}}{W_{ph}} = 6.879 \cdot MPa \qquad \sigma_{ULS.h.wv} := \frac{M_{wh.v}}{W_{ph}} = 2.064 \cdot MPa$$

$$\sigma_{ULS.v.wm} := \frac{N_{ULS.wm}}{h_p \cdot b_p} = 6.294 \cdot MPa \qquad \sigma_{ULS.v.imp} := \frac{N_{ULS}}{h_p \cdot b_p} = 6.82 \cdot MPa$$

$$\boxed{\frac{\sigma_{ULS.v.wm}}{f_{c.0.d} \cdot k_c} + k_m \cdot \frac{\sigma_{ULS.h.wm}}{f_{m.d.30}} = 77.226 \cdot \%}$$

OK!!

$$\boxed{\frac{N_{ULS.wm}}{k_c \cdot N_{c.0.Rd}} + k_m \cdot \frac{M_{wh.m}}{M_{Rd.p}} = 93.25 \cdot \%}$$

OK!!

Mid column inside the preschool

$L_p := 3.05m$

$b_p := 160mm \qquad h_p := 160mm \qquad I_p := \frac{b_p \cdot h_p^{\,3}}{12} = 5.461 \times 10^{-5}\, m^4$

$E_{0.05} := 11300MPa \qquad \beta_c := 0.1 \qquad l_{ef} := L_p = 3.05\, m$

$f_{c.0k} := 24.5MPa \qquad f_{c.0.d} := k_{mod} \cdot \frac{f_{c.0k}}{\gamma_M} = 15.68 \cdot MPa$

$f_{m.k.30} := 30MPa \qquad f_{m.d.30} := k_{mod} \cdot k_h \cdot \frac{f_{m.k.30}}{\gamma_M} = 19.403 \cdot MPa$

$$N_{cr} := \frac{\pi^2 \cdot E_{0.05} \cdot I_p}{L_p^{\,2}} = 654.753 \cdot kN$$

Capacity of compression

$$i := \sqrt{\frac{I_p}{b_p \cdot h_p}} = 0.046\,m$$

$$\lambda := \frac{l_{ef}}{i} = 66.034$$

$$\lambda_{rel} := \frac{\lambda}{\pi} \cdot \sqrt{\frac{f_{c.0k}}{E_{0.05}}} = 0.979$$

$$k := 0.5 \cdot \left[1 + \beta_c \cdot \left(\lambda_{rel} - 0.3\right) + \lambda_{rel}^2\right] = 1.013$$

$$k_c := \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^2}} = 0.785$$

$$N_{c.0.Rd} := f_{c.0.d} \cdot b_p \cdot h_p \cdot k_c = 315.141 \cdot kN$$

Loads

$$A_{bj} := \frac{(6.446 + 5.165)}{2} \cdot \frac{(6 + 6.2)}{2} \cdot m^2 = 35.414\,m^2$$

$$N_{ULS} := \left(1.35 \cdot g_{slab} + 1.5 \cdot q_{imp} \cdot \alpha_A + 1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj} = 296.179 \cdot kN$$

$$N_{ULS.wm} := \left(1.35 \cdot g_{slab} + 1.5 \cdot q_{imp} \cdot \alpha_A \cdot \psi_{0.imp} + 1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w\right) \cdot A_{bj} = 277.385 \cdot kN$$

$$\boxed{\frac{N_{ULS}}{N_{c.0.Rd}} = 93.983 \cdot \%}$$

Column Level 2 - Outer wall

$$L_p := 3.06m$$

$b_p := 140mm$ $\quad$ $h_p := 140mm$ $\quad$ $I_p := \frac{b_p \cdot h_p^3}{12} = 3.201 \times 10^{-5}\,m^4$

$E_{0.05} := 11300MPa$ $\quad$ $\beta_c := 0.1$ $\quad$ $l_{ef} := L_p = 3.06\,m$

$f_{c.0k} := 24.5MPa$ $\qquad f_{c.0.d} := k_{mod} \cdot \frac{f_{c.0k}}{\gamma_M} = 15.68 \cdot MPa$

$f_{m.k.30} := 30MPa$ $\qquad f_{m.d.30} := k_{mod} \cdot k_h \cdot \frac{f_{m.k.30}}{\gamma_M} = 19.403 \cdot MPa$

$$N_{cr} := \frac{\pi^2 \cdot E_{0.05} \cdot I_p}{L_p^{\,2}} = 381.299 \cdot kN$$

Capacity of compression

$$i := \sqrt{\frac{I_p}{b_p \cdot h_p}} = 0.04\,m$$

$$\lambda := \frac{l_{ef}}{i} = 75.715$$

$$\lambda_{rel} := \frac{\lambda}{\pi} \cdot \sqrt{\frac{f_{c.0k}}{E_{0.05}}} = 1.122$$

$$\sigma_{crit} := \frac{0.78 \cdot b_p^{\,2} \cdot E_{0.05}}{h_p \cdot L_p} = 4.033 \times 10^8 \cdot Pa$$

$$\lambda_{rel.m.p} := \sqrt{\frac{f_{m.k.30}}{\sigma_{crit}}} = 0.273$$

$$k := 0.5 \cdot \left[1 + \beta_c \cdot \left(\lambda_{rel} - 0.3\right) + \lambda_{rel}^{\,2}\right] = 1.171$$

$$k_c := \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^{\,2}}} = 0.665$$

$$N_{c.0.Rd} := f_{c.0.d} \cdot b_p \cdot h_p \cdot k_c = 204.265 \cdot kN$$

Loads

$$A_{bj} := \frac{(6.446)}{2} \cdot \frac{(6+6.2)}{2} \cdot m^2 = 19.66\,m^2$$

$$N_{ULS} := \left(1.35 \cdot G_{eg} + 1.5 \cdot S_3 + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj} = 77.66 \cdot kN$$

$$N_{ULS.wm} := \left(1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w\right) \cdot A_{bj} = 70.152 \cdot kN$$

$$\boxed{\frac{N_{ULS}}{N_{c.0.Rd}} = 38.019 \cdot \%}$$

Horizontal wind load

$c_{ez} := 1.54 \frac{kN}{m^2}$ $\quad q_b := 0.39$ $\quad q_p := c_{ez} \cdot q_b = 0.601 \cdot \frac{kN}{m^2}$ $\quad c_{pe} := 0.7$

$$q_w := q_p \cdot c_{pe} = 0.42 \cdot \frac{kN}{m^2}$$

$$k_m := 0.7$$

$q_{wh.m} := q_w \cdot 1.5 = 0.631 \cdot \frac{kN}{m^2}$ $\quad q_{wh.v} := 1.5 \cdot \psi_w \cdot q_w = 0.189 \cdot \frac{kN}{m^2}$

$$M_{wh.m} := \frac{q_{wh.m} \cdot \frac{(6+6.2)}{2} m \cdot L_p^{\,2}}{8} = 4.503 \cdot kN \cdot m$$

$$M_{wh.v} := \frac{q_{wh.v} \cdot \frac{(6+6.2)}{2} m \cdot L_p^{\,2}}{8} = 1.351 \cdot kN \cdot m$$

$W_{ph} := \frac{h_p \cdot \left(b_p\right)^2}{6} = 4.573 \times 10^{-4} \cdot m^3$ In weak direction

$$k_{crit} := \begin{cases} 1 & \text{if } \lambda_{rel.m.p} \le 0.75 \\ (1.56 - 0.75 \cdot \lambda_{rel.m.p}) & \text{if } 0.75 < \lambda_{rel.m.p} \le 1.4 \\ \dfrac{1}{\lambda^2} & \text{otherwise} \end{cases} = 1$$

$$M_{Rd.p} := f_{m.d.30} \cdot W_{ph} \cdot k_{crit} = 8.874 \cdot kN \cdot m$$

$$\boxed{M_{uti.1} := \frac{M_{wh.m}}{M_{Rd.p}} = 50.74 \cdot \%}$$

$$\sigma_{ULS.h.wm} := \frac{M_{wh.m}}{W_{ph}} = 9.845 \cdot MPa \qquad \sigma_{ULS.h.wv} := \frac{M_{wh.v}}{W_{ph}} = 2.954 \cdot MPa$$

$$\sigma_{ULS.v.wm} := \frac{N_{ULS.wm}}{h_p \cdot b_p} = 3.579 \cdot MPa \qquad \sigma_{ULS.v.imp} := \frac{N_{ULS}}{h_p \cdot b_p} = 3.962 \cdot MPa$$

$$\boxed{\frac{\sigma_{ULS.v.wm}}{f_{c.0.d} \cdot k_c} + k_m \cdot \frac{\sigma_{ULS.h.wm}}{f_{m.d.30}} = 0.699}$$

OK!!

$$\boxed{\frac{N_{ULS.wm}}{k_c \cdot N_{c.0.Rd}} + k_m \cdot \frac{M_{wh.m}}{M_{Rd.p}} = 87.19 \cdot \%}$$

OK!!

Mid column floor 2

$$L_p := 3.11m$$

$$b_p := 140mm \qquad h_p := 140mm \qquad I_p := \frac{b_p \cdot h_p^3}{12} = 3.201 \times 10^{-5}\, m^4$$

$$E_{0.05} := 11300MPa \qquad \beta_c := 0.1 \qquad l_{ef} := L_p = 3.11\, m$$

$f_{c.0k} := 24.5MPa$ $\qquad$ $f_{c.0.d} := k_{mod} \cdot \frac{f_{c.0k}}{\gamma_M} = 15.68 \cdot MPa$

$f_{m.k.30} := 30MPa$ $\qquad$ $f_{m.d.30} := k_{mod} \cdot k_h \cdot \frac{f_{m.k.30}}{\gamma_M} = 19.403 \cdot MPa$

$$N_{cr} := \frac{\pi^2 \cdot E_{0.05} \cdot I_p}{L_p^2} = 369.138 \cdot kN$$

Capacity of compression

$$i := \sqrt{\frac{I_p}{b_p \cdot h_p}} = 0.04\,m$$

$$\lambda := \frac{l_{ef}}{i} = 76.953$$

$$\lambda_{rel} := \frac{\lambda}{\pi} \cdot \sqrt{\frac{f_{c.0k}}{E_{0.05}}} = 1.141$$

$$k := 0.5 \cdot \left[1 + \beta_c \cdot \left(\lambda_{rel} - 0.3\right) + \lambda_{rel}^2\right] = 1.192$$

$$k_c := \frac{1}{k + \sqrt{k^2 - \lambda_{rel}^2}} = 0.649$$

$$N_{c.0.Rd} := f_{c.0.d} \cdot b_p \cdot h_p \cdot k_c = 199.505 \cdot kN$$

Loads

$$A_{bj} := \frac{(6.446 + 5.165)}{2} \cdot \frac{(6 + 6.2)}{2} \cdot m^2 = 35.414\,m^2$$

$$N_{ULS} := \left(1.35 \cdot G_{eg} + 1.5 \cdot S_3 + 1.5 \cdot Q_w \cdot \psi_w\right) \cdot A_{bj} = 139.887 \cdot kN$$

$$N_{ULS.wm} := \left(1.35 \cdot G_{eg} + 1.5 \cdot S_3 \cdot \psi_S + 1.5 \cdot Q_w\right) \cdot A_{bj} = 126.363 \cdot kN$$

$$\boxed{\frac{N_{ULS}}{N_{c.0.Rd}} = 70.117 \cdot \%}$$

Columns

B
Actions on structures

B.1 Actions on structures 2019

September 2019

Appendices A-E
Actions on Structures and Combination of Loads

Available aids, if relevant, at the exams in the Masters Programme “Structural Engineering and Building performance Design”. The aim is to prepare students for their future careers and help them understand and apply the principles of Eurocode 1.

Table 2.8 Design values of actions for equilibrium (EQU) and strength (STR) limit states*

Ultimate limit state (under persistent and transient design situations – fundamental combinations)		Relevant equation in EC0	Permanent actions		Leading variable action	Accompanying variable actions	
			Unfavourable[‖]	Favourable[‖]		Main	Others
EQU	(a)[†]	*(6.10)*	$1.10G_{k,j,sup}$	$0.90G_{k,j,inf}$	$1.5Q_{k,1}$ (0 when favourable)	–	$1.5\psi_{0,i}Q_{k,i}$ (0 when favourable)
	(b)[‡] The highest design value from combination (i) or (ii)	(i) *(6.10)*	$1.35G_{k,j,sup}$	$1.15G_{k,j,inf}$	$1.5Q_{k,1}$ (0 when favourable)	–	$1.5\psi_{0,i}Q_{k,i}$ (0 when favourable)
		(ii) *(6.10)*	$1.0G_{k,j,sup}$	$1.0G_{k,j,inf}$	$1.5Q_{k,1}$ (0 when favourable)	–	$1.5\psi_{0,i}Q_{k,i}$ (0 when favourable)
STR[§] (not involving geotechnical actions)	(c)	(i) *(6.10)*	$1.35G_{k,j,sup}$	$1.0G_{k,j,inf}$	$1.5Q_{k,1}$ (0 when favourable)	–	$1.5\psi_{0,i}Q_{k,i}$ (0 when favourable)
	(d)	(ii) *(6.10a)*	$1.35G_{k,j,sup}$	$1.0G_{k,j,inf}$	–	$1.5\psi_{0,1}Q_{k,1}$	$1.5\psi_{0,i}Q_{k,i}$
		(iii) *(6.10b)*	$0.925 \times 1.35G_{k,j,sup}$	$1.0G_{k,j,inf}$	$1.5Q_{k,1}$	–	$1.5\psi_{0,i}Q_{k,i}$

Appendix A: Combination of loads

Fundamental combination, ULS STR, cf. Table 2.8, Eq. 6.10.

$$\sum_{j\geq 1} \gamma_{G,j} G_{k,j} \text{"+"} \gamma_P P \text{"+"} \gamma_{Q,1} Q_{k,1} \text{"+"} \sum_{i>1} \gamma_{Q,i} \psi_{0,i} Q_{k,i}$$

Characteristic combination, SLS

$$\sum_{i} G_{k,i} + Q_{k,1} + \sum_{j>1} \psi_{0,j} Q_{k,j}$$

Quasi-permanent combination, SLS

$$\sum_{i} G_{k,i} + \sum_{j\geq 1} \psi_{2,j} Q_{k,j}$$

Partial safety factors γ_f for permanent and variable loads (ULS and SLS)

Design situation	ULS		SLS	
	Permanent action γ_g	Variable action γ_q	Permanent action γ_g	Variable action γ_q
Fundamental favourable unfavourable	 1.0 1.35	 0 1.5	 1.0 1.0	 0 1.0
Accidental	1.0	1.0	-	-

ACTION	ψ_0	ψ_1	ψ_2
Imposed load			
Categ. A, B	0.7	0.5	0.3
Categ. C, D	0.7	0.7	0.6
Categ. E	1.0	0.9	0.8
Wind load	0.3	0.2	0
***Snow load**			
$s_k \geq 3$ kN/m^2	0.8	0.6	0.2
$2.0 \leq s_k < 3.0$ kN/m^2	0.7	0.4	0.2
$1.0 \leq s_k < 2.0$ kN/m^2	0.6	0.3	0.1

* These coefficients are applicable to Scandinavian countries

Appendix B: Imposed loads

category		imposed loads		ψ-coefficients			→ horizontal loads
		q_k [kN/m²]	Q_k [kN]	ψ_0	ψ_1	ψ_2	q_k [kN/m]
A	areas for domestic and residential activities						
	general	2.0	2.0	0.7	0.5	0.3	0.5
	stairs	3.0					
	balconies	4.0					
B	office areas	3.0	2.0	0.7	0.5	0.3	1.0
C	areas where people may congregate						
C1	Areas with tables (e.g., in schools, cafés, restaurants, dining halls, reading rooms, receptions)	3.0	4.0	0.7	0.7	0.6	1.0
C2	Areas with fixed seats (e.g., areas in churches, theatres, cinemas, conference rooms, lecture halls, assembly halls, waiting rooms)	4.0	4.0				1.5 [a])
C3	Areas without obstacles for moving people (e.g., areas in museums, exhibition rooms, and access areas – e.g. in public and administration buildings, hotels)	5.0	4.0				1.5 [a])
C4	Areas with possible physical activities (e.g., dance halls, gymnastic rooms, stages)	5.0	7.0				1.5 [a])
C5	Areas susceptible to overcrowding (e.g., in buildings for public events like concert halls, sport halls including stands, terraces and access areas)	5.0	4.0				3.0
D	Shopping areas						
D1	areas in general retails shops	5.0	4.0	0.7	0.7	0.6	1.5
D2	Areas in department stores (e.g., areas in warehouses, stationery, and office stores)	5.0	7.0	0.7	0.7	0.6	1.5
E	Areas for storage including libraries						
	Only minimum loads given, further guidance see 4.6	6.0	7.0	1.0	0.9	0.8	

[a]) for areas susceptible to overcrowding associated with public events the line load should be taken according to category C5

The self-weight of movable partitions may be taken into account as a uniformly-distributed load q_k which should be added to the imposed loads (Cat. A to D) of floors obtained from this table.

Appendix B: Imposed loads

Imposed loads (ULS)

$$\alpha_A = \frac{5}{7}\psi_0 + \frac{A_0}{A} \leq 1.0$$ EN 1991-1-1 (6.1)

where:

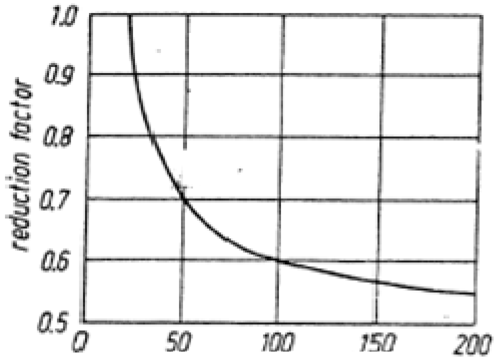
ψ_0 is the factor according to EN 1990 Annex A1

$A_0 = 10{,}0\text{m}^2$

A is the loaded area

Imposed loads q_k may be reduced (for categories A-E) by applying a reduction factor α_A

$\alpha_A = 0.5 + 10/A[\text{m}^2] \leq 1$ for categories A – D ($\psi_0 = 0.7$)



Factor α_A as a function of A

$$\alpha_n = \frac{2 + (n-2)\,\psi_0}{n}$$ EN 1991-1-1 (6.2)

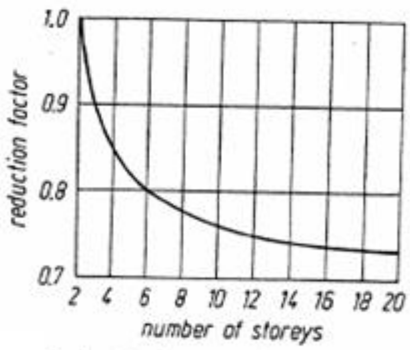
where

n number of stories *above* the loaded element

ψ_0

α_n accounts for the fact that it is unlikely that loads on several floors attain high values at the same time.

Imposed loads q_k from more than two storeys may be reduced (for categories A-D) by applying a reduction factor α_n

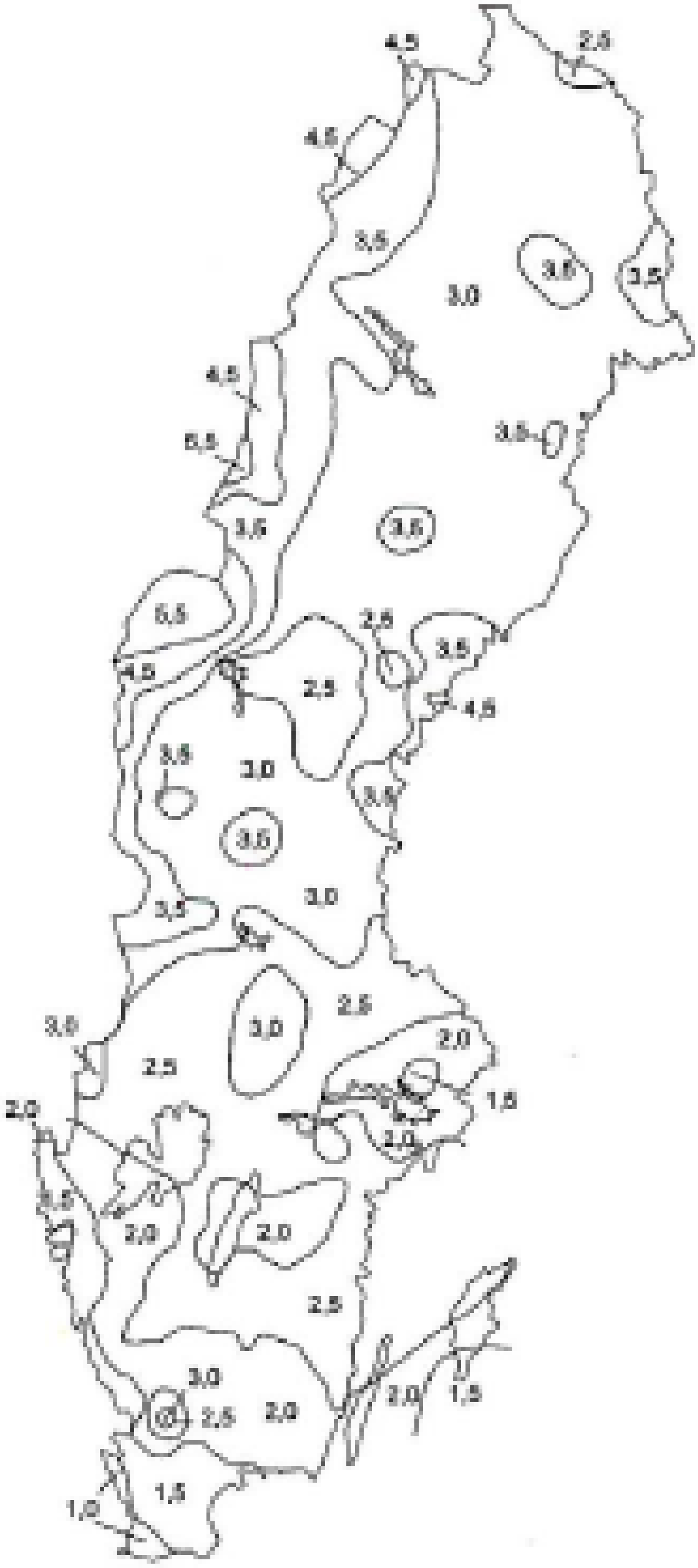


Reduction factor α_n for $\psi_0 = 0.7$

- The reduction factors α_A and α_n must NOT be combined. For the design of floors and roofs α_A can be used. For structural members that carry imposed loads from several stories α_n can be taken and the imposed loads can be assumed as uniformly distributed.
- When the imposed load is considered as an accompanying action, only ψ_0 shall be applied.

Appendix C: Snow loads

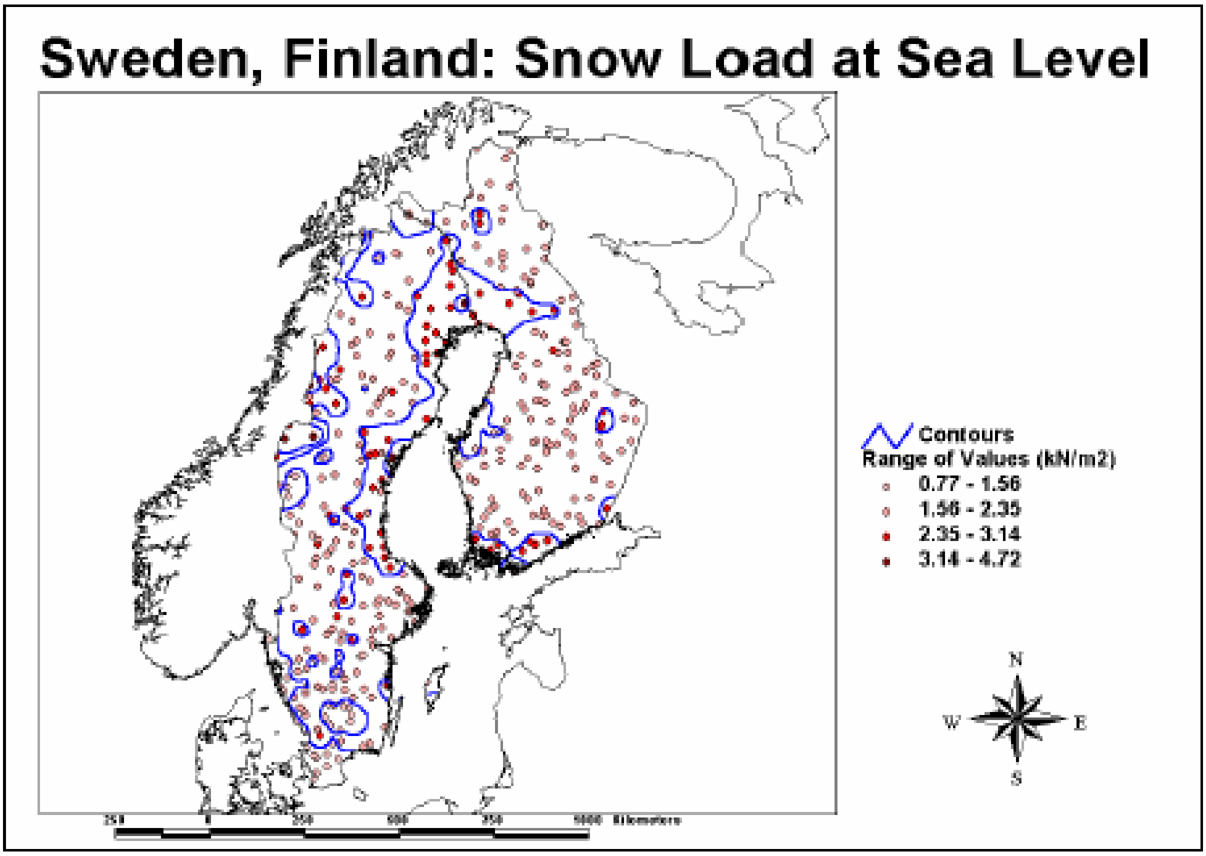
EN 1991-1-3:2003 (BFS 2008:19)

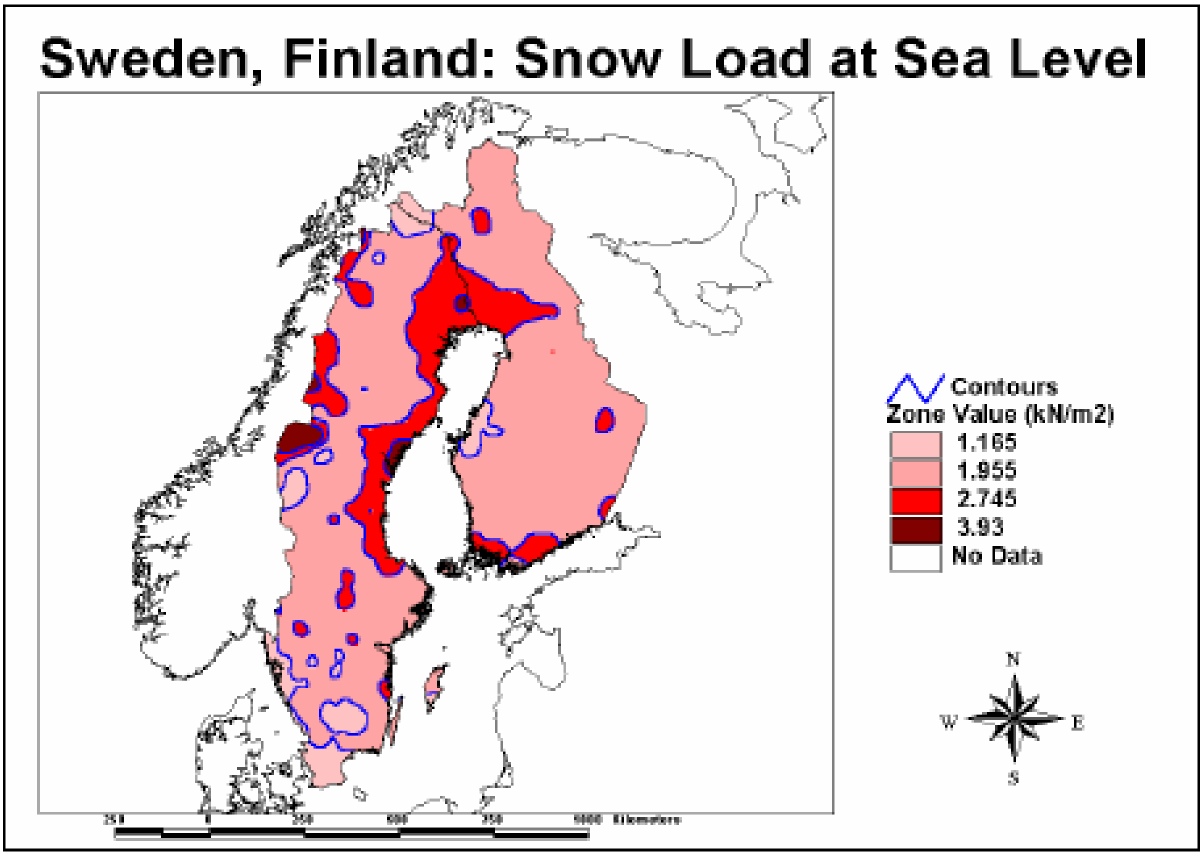


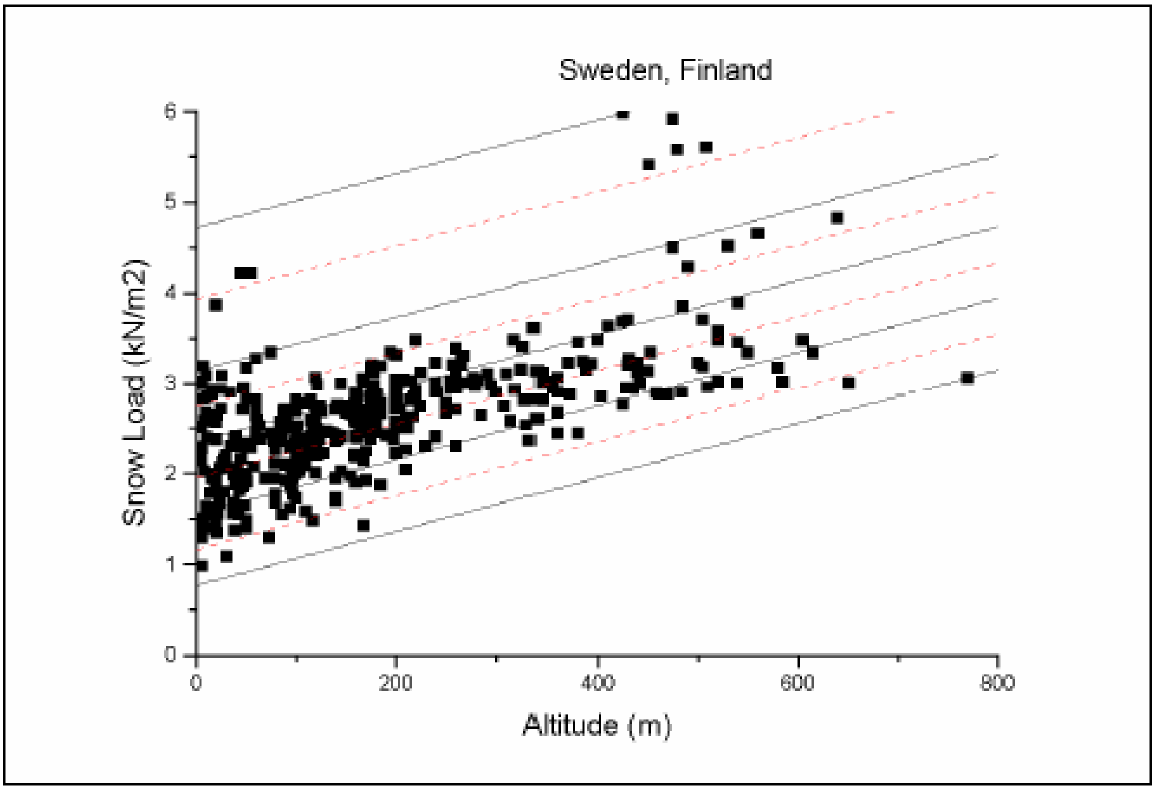
Characteristic snow values s_k for some Swedish town (urban) districts	
Alingsås	2.0
Arvika	2.5
Borås	2.0-2.5
Borlänge	3.0
Falun	2.5-3.0
Gällivare	3.0-4.5
Göteborg	1.5
Halmstad	1.5-2.5
Haparanda	3.0
Hofors	2.5
Härnösand	3.5
Jokkmokk	3.0-4.5
Jönköping	2.5-3.0
Karlstad	2.5
Kiruna	2.5-4.5
Kungälv/ Kungsbaka	1.5
Landskrona	1.0
Luleå	3.0
Lund	1.5
Malmö	1.0
Stockholm	2.0
Örebro	2.5
Östersund	2.0-3.5

The upper values of the intervals apply to terrain in high places.

CLIMATIC REGION: SWEDEN, FINLAND







(black line = zone limit)
(red line = representative altitude - snow load relationship for the corresponding zone)

PARAMETERS:

Climatic Region	Function Type	a_{min}	a_{max}	b
Sweden, Finland	**L**	0.77	4.72	336

Zone Number (Scatter Plot)	Z=1	Z=2	Z=3	Z=4.5
r	0.96	0.86	0.88	0.91

r = correlation coefficient (snow load values / representing function)
H = horizontal line, no altitude - snow load relationship
L = linear function
Q = quadratic function

REPRESENTATIVE SNOW LOAD FOR ZONE Z AT ALTITUDE A:

$$s = (0.77 + (Z - 0.5) * [4.72 - 0.77] / 5) + \frac{A}{336}$$

s = Snow Load (KN/m^2)
A = Altitude above Sea Level (m)
Z = Zone Number

Appendix C: Characteristic value of snow load:

$S = \mu_i C_e C_t s_k \qquad s = \mu_i s_k$

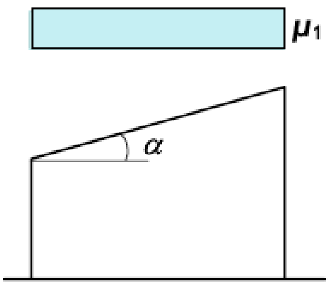
s_k characteristic value of snow on the ground,

C_e exposure coefficient, should be taken as 1.0 unless otherwise specified for different topographies

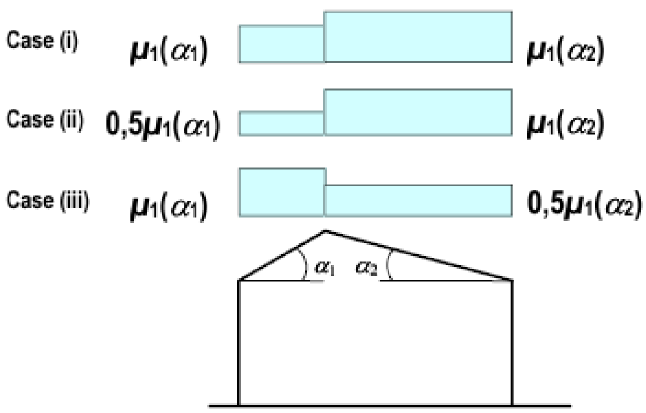
C_t thermal coefficient, high thermal transmittance (> 1 W/m2K), in particular for some glass covered roofs, because of melting caused by heat loss. For all other cases: C_t = 1.0

μ_i shape coefficients

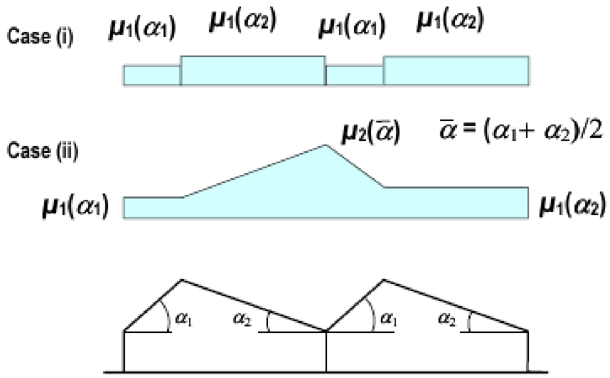
Monopitch roofs

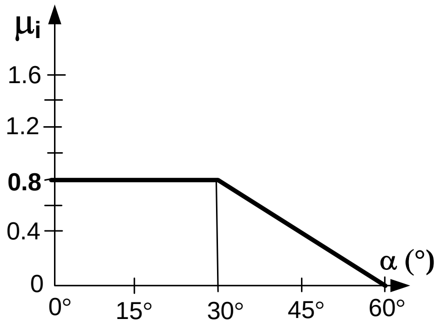


Pitched roofs



Multi-span roofs





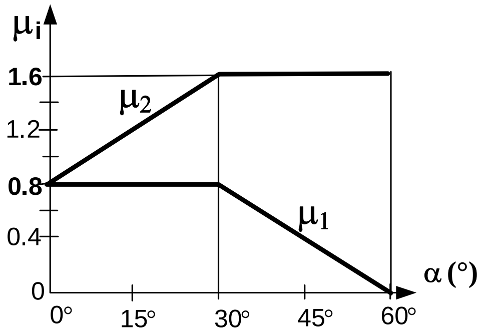
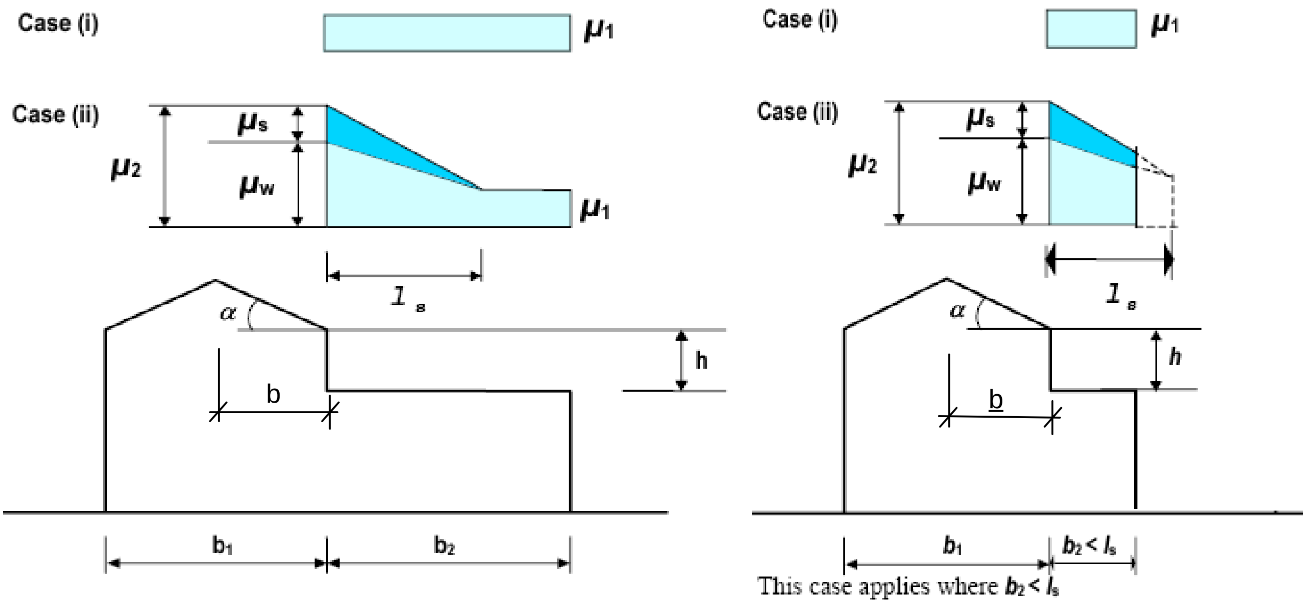


Table 5.2: Snow load shape coefficients

Angle of pitch of roof α	$0° \leq \alpha \leq 30°$	$30° < \alpha < 60°$	$\alpha \geq 60°$
μ_1	0,8	$0,8(60 - \alpha)/30$	0,0
μ_2	$0,8 + 0,8\ \alpha/30$	1,6	--

Appendix C

Roofs abutting to taller construction works



μ_1 = 0,8 (assuming the lower roof is flat)

$\mu_2 = \mu_S + \mu_W$

Shape coefficients

$\mu_2 = \mu_S + \mu_W$

μ_S due to sliding of snow from the upper roof

μ_W due to wind

For $\alpha \leq 15°$ $\mu_S = 0$

$\alpha > 15°$ μ_S is determined from an additional load amounting to 50% of the maximum total snow load, on the on the adjacent slope of the upper roof

$\mu_w = (b_1 + b_2)/2h \leq \gamma\ h/s_k$

where: γ is the weight density of snow, which may be taken as 2 kN/m^3. $0.8 \leq \mu_w \leq 4$

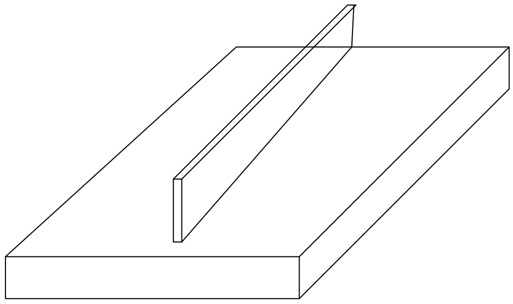
The drift length: $l_S = 2h$. The recommended restriction is $5 \leq l_S \leq 15$ m.

(In Sweden $5 \leq l_S \leq 10$ m)

Appendix C

Drifting at projections and obstructions

Drift against a wall



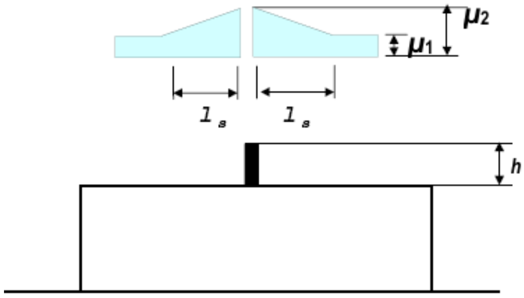
Shape coefficients μ

$\mu_1 = 0{,}8 \quad \mu_2 = \gamma\, h/s_k$

With the restriction: $0{,}8 \leq \mu_2 \leq 2{,}0$

The drift length: $l_S = 2h$

With the restriction is $5 \leq l_S \leq 10$ m



Appendix D1: Wind loads

EN 1991-1-4, April 2005

Wind pressure on surfaces

Wind pressure on external surfaces (w_e) and internal surfaces (w_i) should be calculated to

External pressure:

$$w_e = q_p(z_e) \cdot c_{pe}$$

Internal pressure:

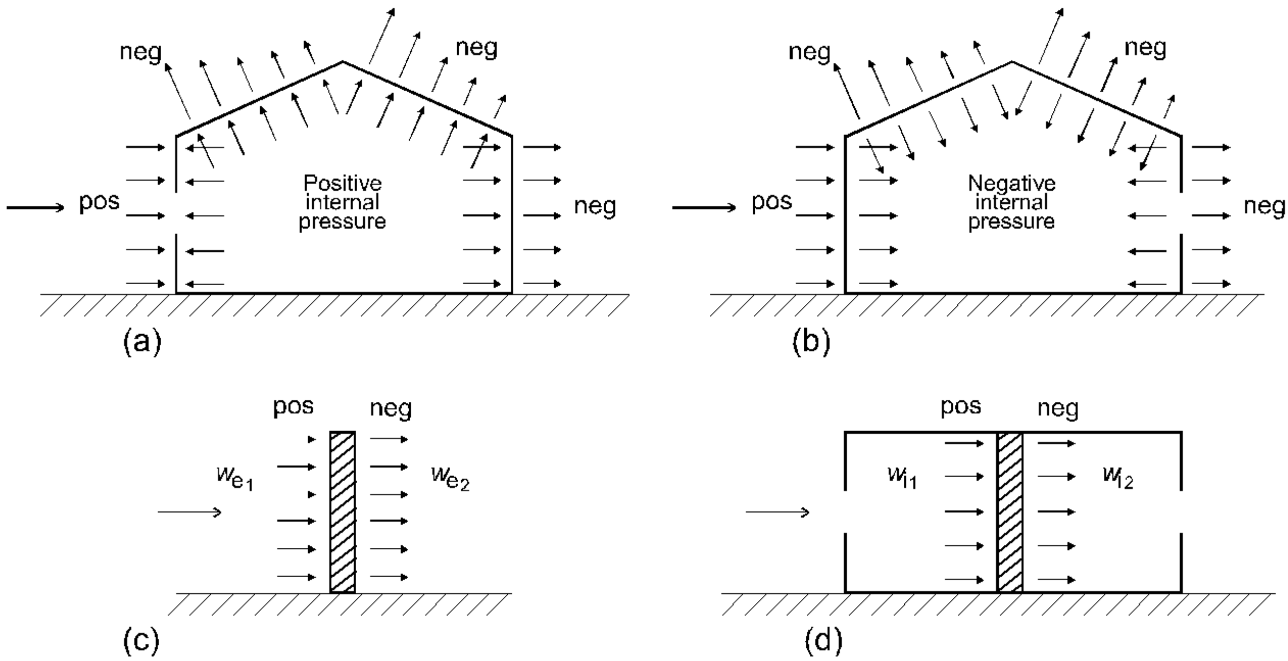
$$w_i = q_p(z_e) \cdot c_{pi}$$

where: $q_p(z_e)$ is the peak velocity pressure, see D2, which dependents on the reference height, z_e,

c_{pe} and c_{pi} are the pressure coefficients for the external and internal pressure respectively, see D4-D15

Pressure on surfaces

The net pressure on a wall, roof or element is the difference between the pressures on the opposite surfaces taking due account of their signs. Pressure, directed towards the surface is taken as positive, and suction, directed away from the surface as negative.



Wind forces

The wind forces for the whole structure or a structural component should be determined:
– by calculating forces using force coefficients or
– by calculating forces from surface pressures
The wind force F_W acting on a structure or a structural component may be determined directly by using:

$$F_W = c_S c_d c_f q_p(z_e) A_{ref}$$

where c_S, c_d· can for most structures assumed to be 1
c_f is the force coefficient for the structure or structural element.

Appendix D2

Peak velocity pressure

$q_p(z_e) = c_e(z)q_b$

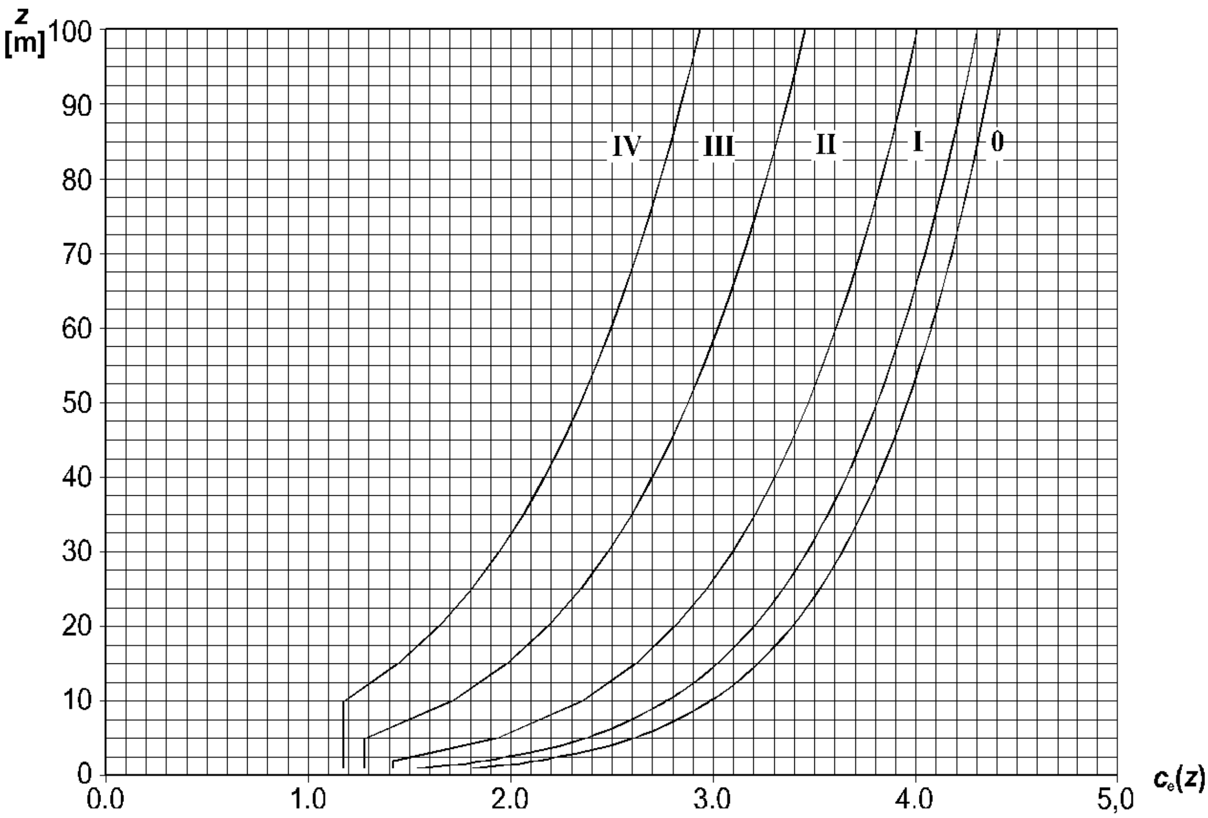
where $c_e(z)$ is the exposure factor, using Table D2 and Figure D2

$q_b = \frac{1}{2}\rho v_b^2 = \frac{v_b^2}{1600}$ is the reference mean (basic) velocity pressure in kN/m², with the recommended value for the air density $\rho = 1.25\ kg/m^3$ and the basic wind velocity, v_b in m/s, according to Appendix D3

Table D2 Terrain categories and terrain parameter

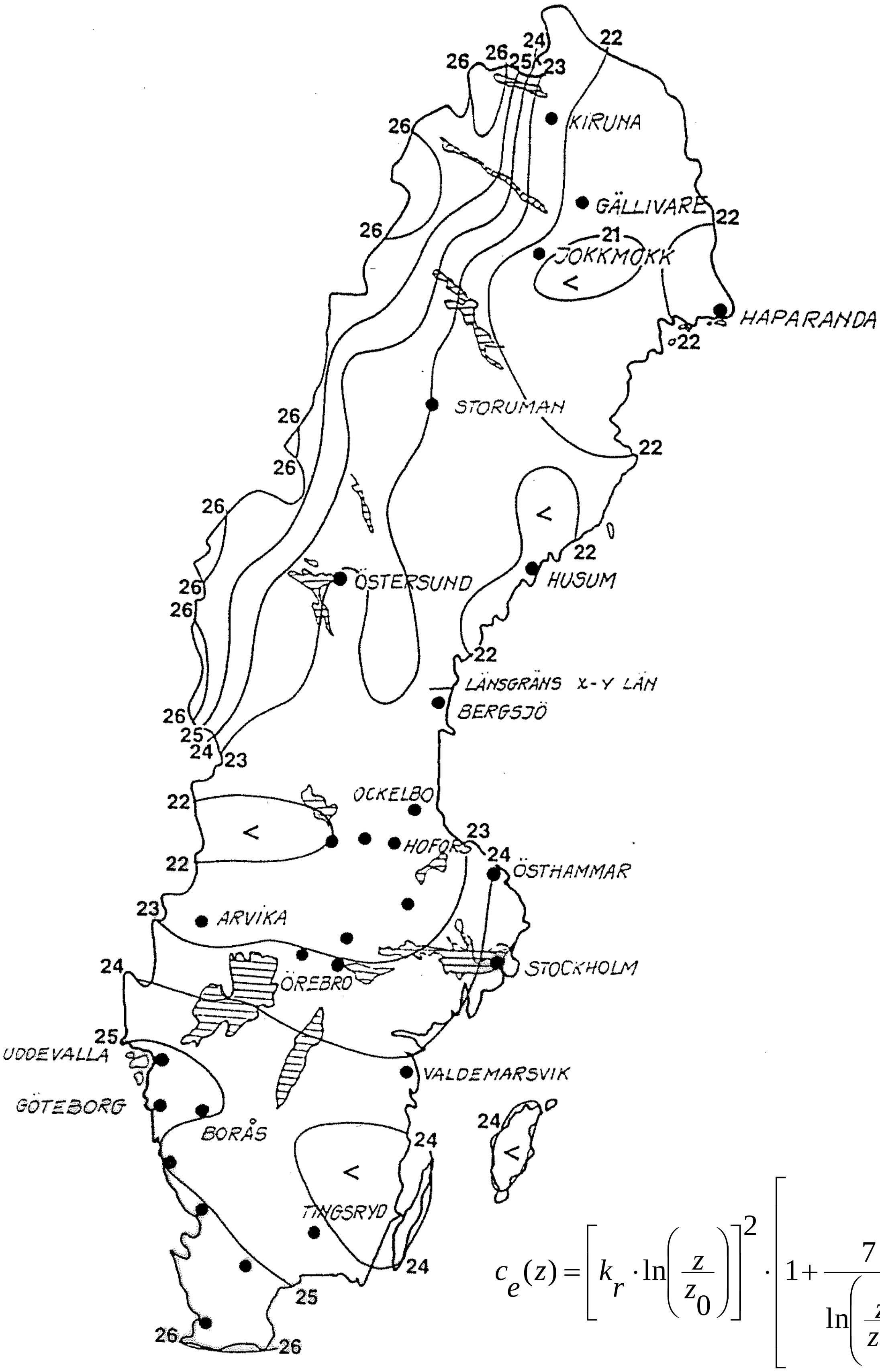
Terrain category		z_0 m	z_{min} m	k_r -
0	Sea or coastal area exposed to the open sea	0,003	1	0,16
I	Lakes or flat and horizontal area with negligible vegetation and without obstacles	0,01	1	0,17
II	Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights	0,05	2	0,19
III	Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest)	0,3	5	0,22
IV	Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m	1,0	10	0,24
NOTE: The terrain categories are illustrated in A.1.				

Figure D2 Illustration of the exposure factor $c_e(z)$ for c_0=1.0



Appendix D3.

Reference wind speed v_b in [m/s] for Sweden



$$c_e(z) = \left[k_r \cdot \ln\left(\frac{z}{z_0}\right) \right]^2 \cdot \left[1 + \frac{7}{\ln\left(\frac{z}{z_0}\right)} \right]$$

Expression above for the exposure factor $c_e(z)$ shown in Fig D2
(Coefficients shown in Table D2)

Appendix D4

Internal pressure coefficients

For a building with a **dominant face the internal pressure** should be taken as a fraction of the external pressure at the openings of the dominant face. The values given by Eq (7.2) and (7.3) should be used.
When the area of the openings at the dominant face is twice the area of the openings in the remaining faces,

$c_{pi} = 0,75 \cdot c_{pe}$ (7.2)

When the area of the openings at the dominant face is at least 3 times the area of the openings in the remaining faces,

$c_{pi} = 0,9 \cdot c_{pe}$ (7.3)

where c_{pe} is the value for the external pressure coefficient at the openings in the dominant face.

For buildings **without a dominant face**, the internal pressure coefficient c_{pi} should be determined from Figure 7.13, and is a function of the ratio of the height and the depth of the building, h/d, and the opening ratio μ for each wind direction θ, which should be determined from Eq (7.4).

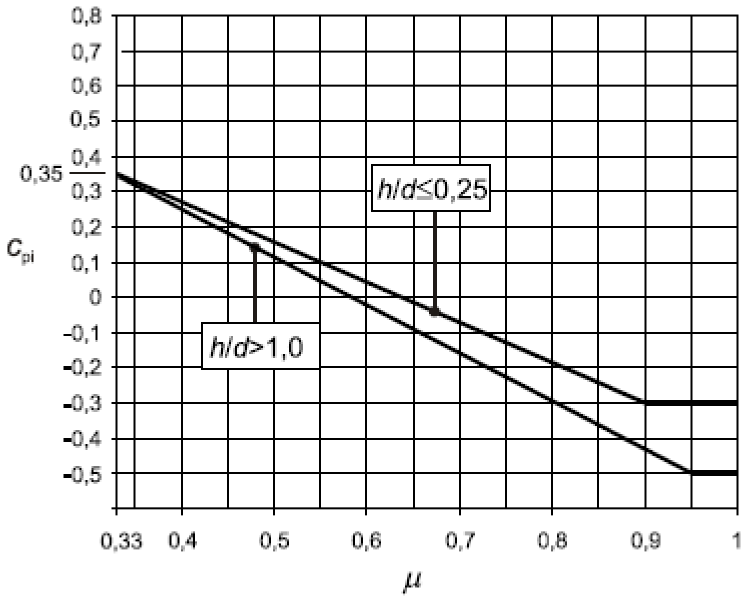


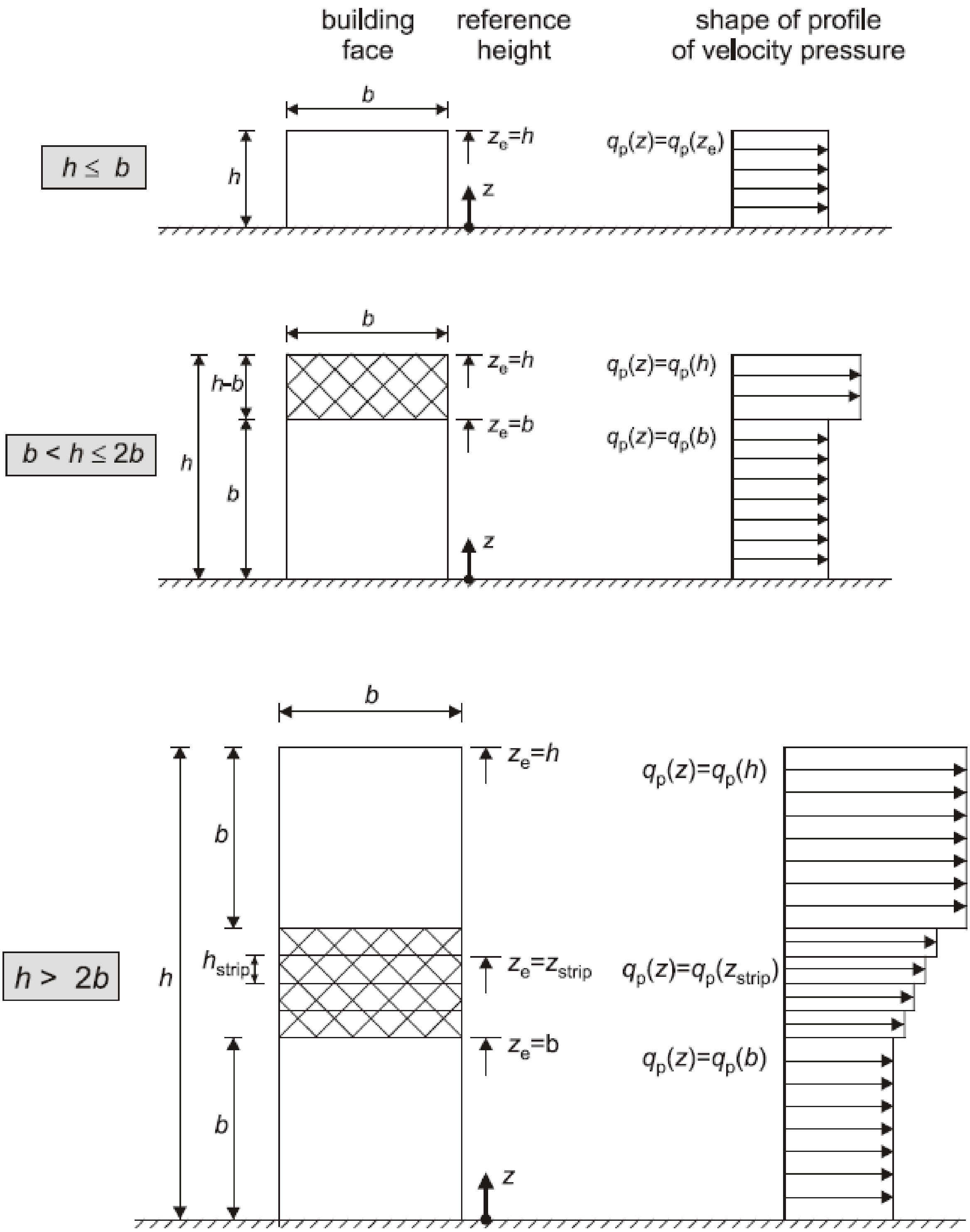
Figure 7.13 — Internal pressure coefficients for uniformly distributed openings

$$\mu = \frac{\sum \text{area of openings where } c_{pe} \text{ is negative or -0,0}}{\sum \text{area of all openings}}$$

If the area of openings is unknown use c_{pi} = + 0.2 or -0.3

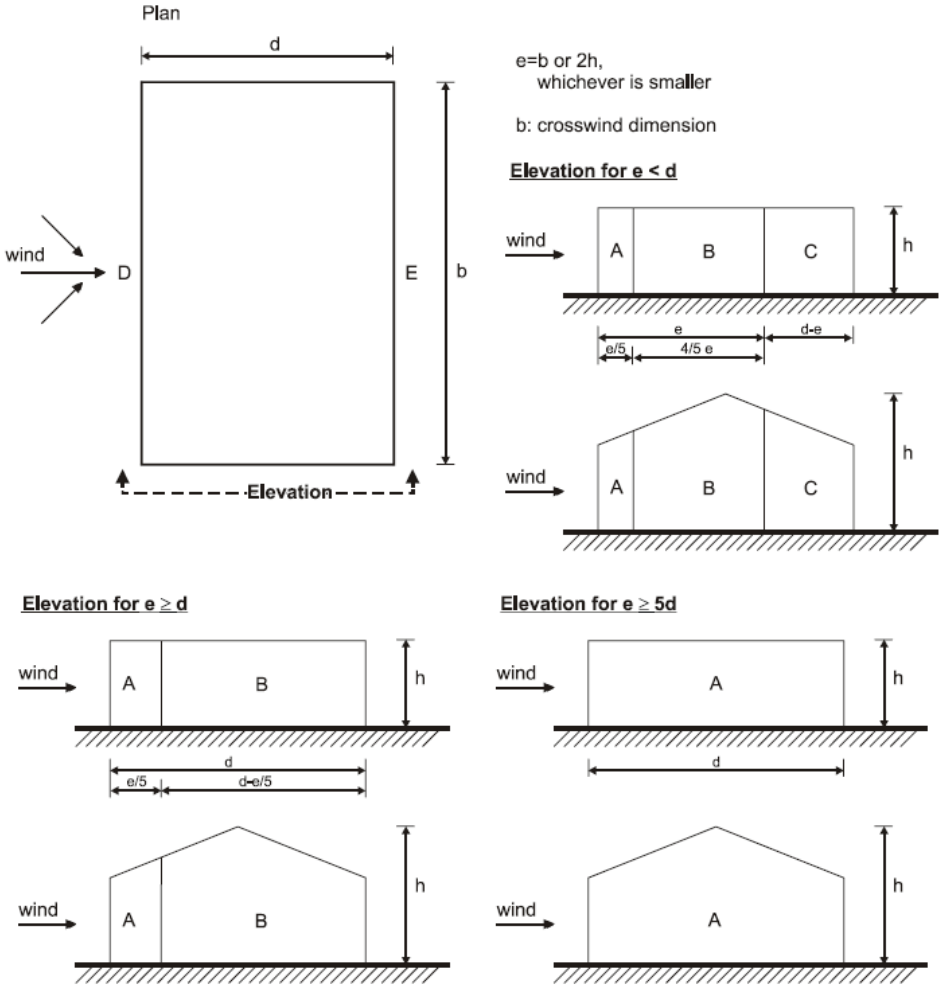
Appendix D5

Reference height, z_e, depending on h and b, and corresponding velocity pressure profile



NOTE The velocity pressure should be assumed to be uniform over each horizontal strip considered.

Appendix D6 Pressure coefficients on the external walls



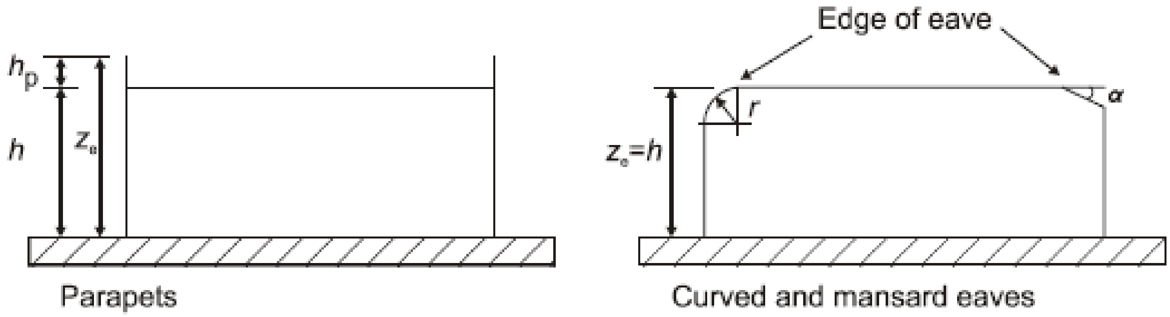
The values of $c_{pe,10}$ and $c_{pe,1}$ may be given in the NA. The recommended values are given in Table below, depending on the ratio *h*/*d*. For intermediate values of *h*/*d*, linear interpolation may be applied. The values of Table also apply to walls of buildings with inclined roofs, such as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

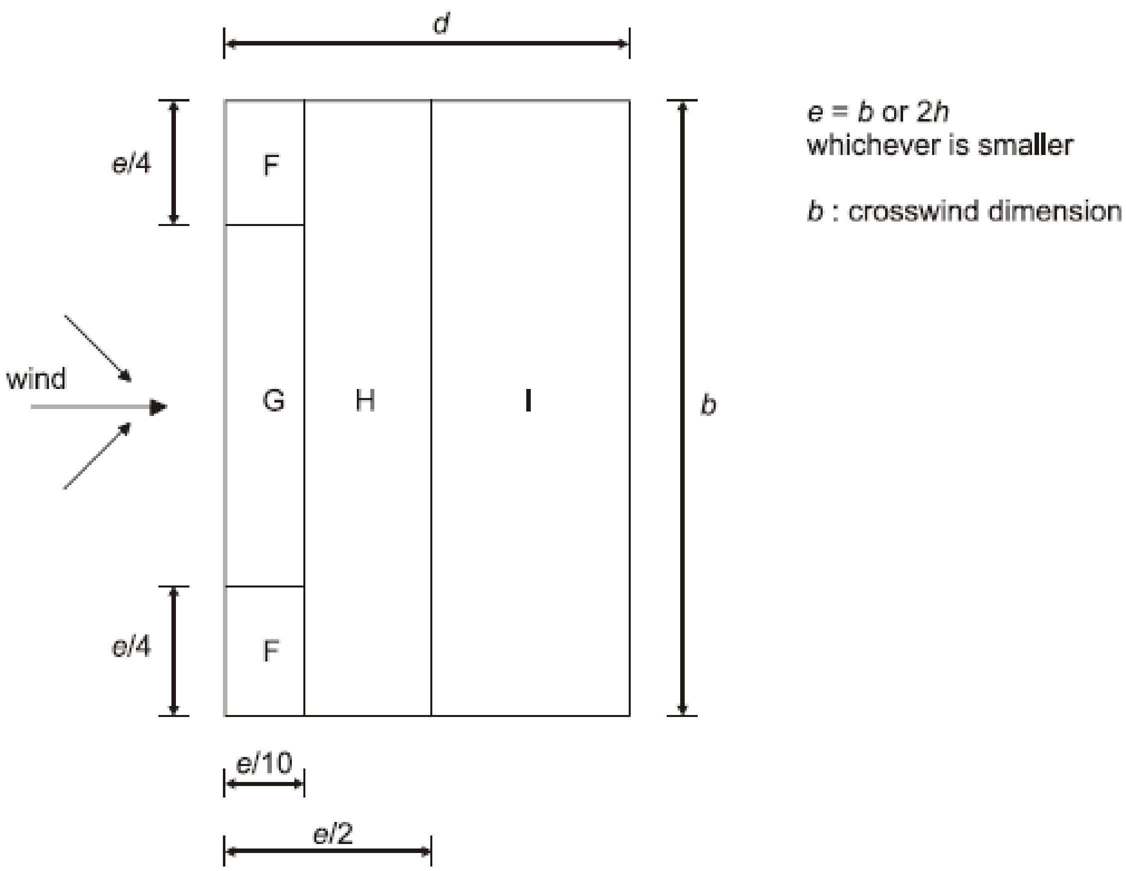
Zone	**A**		**B**		**C**		**D**		**E**	
h/*d*	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$
5	-1,2	-1,4	-0,8	-1,1	-0,5		+0,8	+1,0	-0,7	
1	-1,2	-1,4	-0,8	-1,1	-0,5		+0,8	+1,0	-0,5	
≤ 0,25	-1,2	-1,4	-0,8	-1,1	-0,5		+0,7	+1,0	-0,3	

For intermediate values of *h*/*d*, linear interpolation may be applied.

Appendix D7 Flat roofs

Flat roofs are defined as having a slope (α) of –5°< α < 5°





Appendix D8 Flat roofs

Table 7.2 — External pressure coefficients for flat roofs

Roof type		Zone F $c_{pe,10}$	F $c_{pe,1}$	G $c_{pe,10}$	G $c_{pe,1}$	H $c_{pe,10}$	H $c_{pe,1}$	I $c_{pe,10}$	I $c_{pe,1}$
Sharp eaves		-1,8	-2,5	-1,2	-2,0	-0,7	-1,2	+0,2 -0,2	
With Parapets	h_p/h=0,025	-1,6	-2,2	-1,1	-1,8	-0,7	-1,2	+0,2 -0,2	
	h_p/h=0,05	-1,4	-2,0	-0,9	-1,6	-0,7	-1,2	+0,2 -0,2	
	h_p/h=0,10	-1,2	-1,8	-0,8	-1,4	-0,7	-1,2	+0,2 -0,2	
Curved Eaves	r/h = 0,05	-1,0	-1,5	-1,2	-1,8	-0,4		+0,2 -0,2	
	r/h = 0,10	-0,7	-1,2	-0,8	-1,4	-0,3		+0,2 -0,2	
	r/h = 0,20	-0,5	-0,8	-0,5	-0,8	-0,3		+0,2 -0,2	
Mansard Eaves	α = 30°	-1,0	-1,5	-1,0	-1,5	-0,3		+0,2 -0,2	
	α = 45°	-1,2	-1,8	-1,3	-1,9	-0,4		+0,2 -0,2	
	α = 60°	-1,3	-1,9	-1,3	-1,9	-0,5		+0,2 -0,2	

NOTE 1 For roofs with parapets or curved eaves, linear interpolation may be used for intermediate values of h_p/h and r/h.

NOTE 2 For roofs with mansard eaves, linear interpolation between α = 30°, 45° and α = 60° may be used. For α > 60° linear interpolation between the values for α = 60° and the values for flat roofs with sharp eaves may be used.

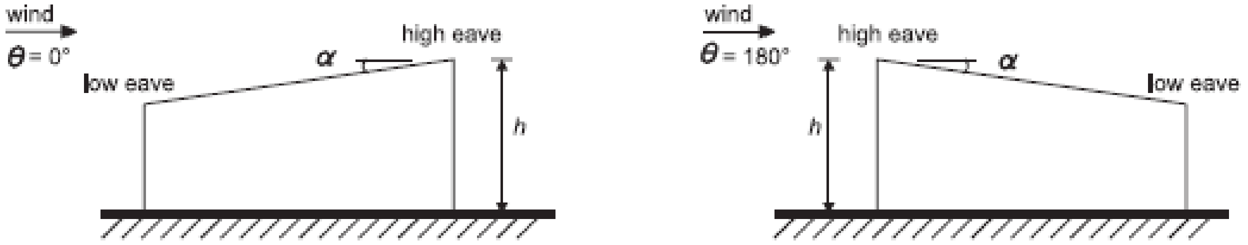
NOTE 3 In Zone I, where positive and negative values are given, both values shall be considered.

NOTE 4 For the mansard eave itself, the external pressure coefficients are given in Table 7.4a "External pressure coefficients for duopitch roofs: wind direction 0° ", Zone F and G, depending on the pitch angle of the mansard eave.

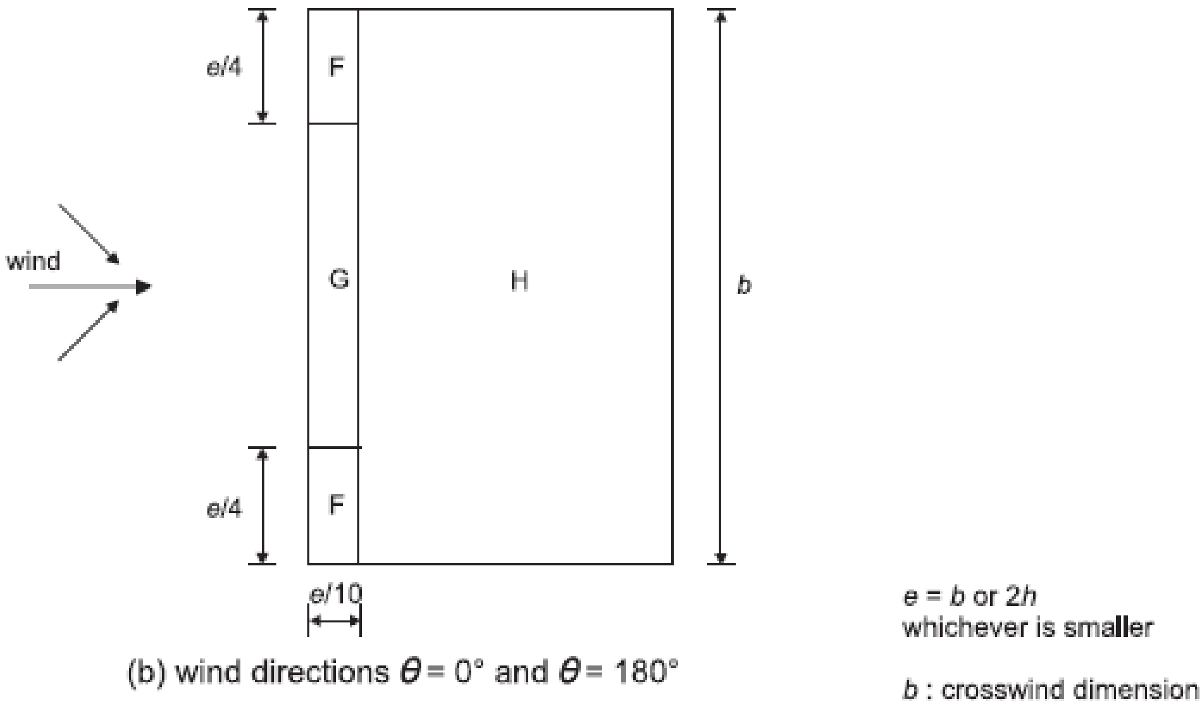
NOTE 5 For the curved eave itself, the external pressure coefficients are given by linear interpolation along the curve, between values on the wall and on the roof.

Appendix D9 Monopitch roofs

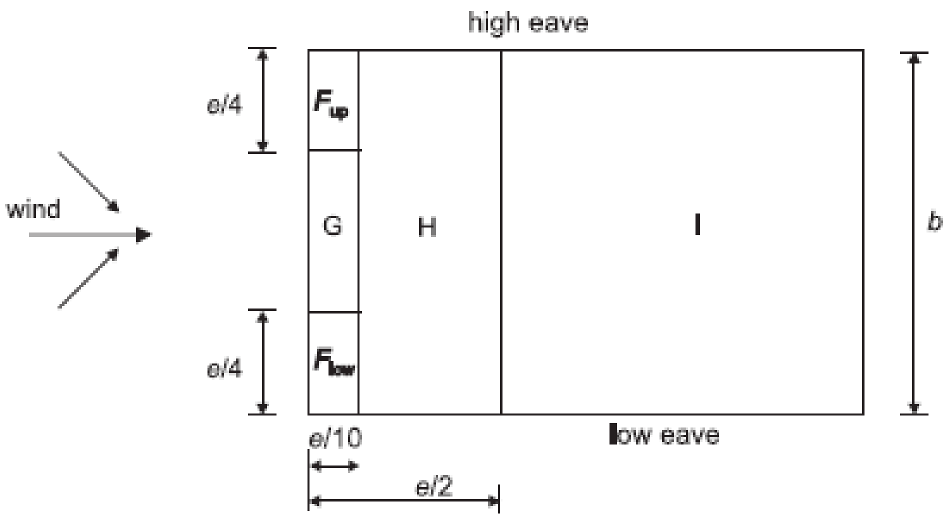
The roof, including protruding parts, should be divided into zones as shown in Figure below. The reference height z_e should be taken equal to h.



(a) general



(b) wind directions $\theta = 0°$ and $\theta = 180°$



(c) wind direction $\theta = 90°$

Appendix D10

Monopitch roofs

Table 7.3a — External pressure coefficients for monopitch roofs

Pitch Angle α	Zone for wind direction $\theta = 0°$						Zone for wind direction $\theta = 180°$					
	F		G		H		F		G		H	
	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$
5°	-1,7	-2,5	-1,2	-2,0	-0,6	-1,2	-2,3	-2,5	-1,3	-2,0	-0,8	-1,2
	+0,0		+0,0		+0,0							
15°	-0,9	-2,0	-0,8	-1,5	-0,3		-2,5	-2,8	-1,3	-2,0	-0,9	-1,2
	+0,2		+0,2		+ 0,2							
30°	-0,5	-1,5	-0,5	-1,5	-0,2		-1,1	-2,3	-0,8	-1,5	-0,8	
	+0,7		+0,7		+0,4							
45°	-0,0		-0,0		-0,0		-0,6	-1,3	-0,5		-0,7	
	+0,7		+0,7		+0,6							
60°	+0,7		+0,7		+0,7		-0,5	-1,0	-0,5		-0,5	
75°	+0,8		+0,8		+0,8		-0,5	-1,0	-0,5		-0,5	

Table 7.3b — External pressure coefficients for monopitch roofs

Pitch Angle α	Zone for wind direction $\theta = 90°$									
	F_{up}		F_{low}		G		H		I	
	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$
5°	-2,1	-2,6	-2,1	-2,4	-1,8	-2,0	-0,6	-1,2	-0,5	
15°	-2,4	-2,9	-1,6	-2,4	-1,9	-2,5	-0,8	-1,2	-0,7	-1,2
30°	-2,1	-2,9	-1,3	-2,0	-1,5	-2,0	-1,0	-1,3	-0,8	-1,2
45°	-1,5	-2,4	-1,3	-2,0	-1,4	-2,0	-1,0	-1,3	-0,9	-1,2
60°	-1,2	-2,0	-1,2	-2,0	-1,2	-2,0	-1,0	-1,3	-0,7	-1,2
75°	-1,2	-2,0	-1,2	-2,0	-1,2	-2,0	-1,0	-1,3	-0,5	

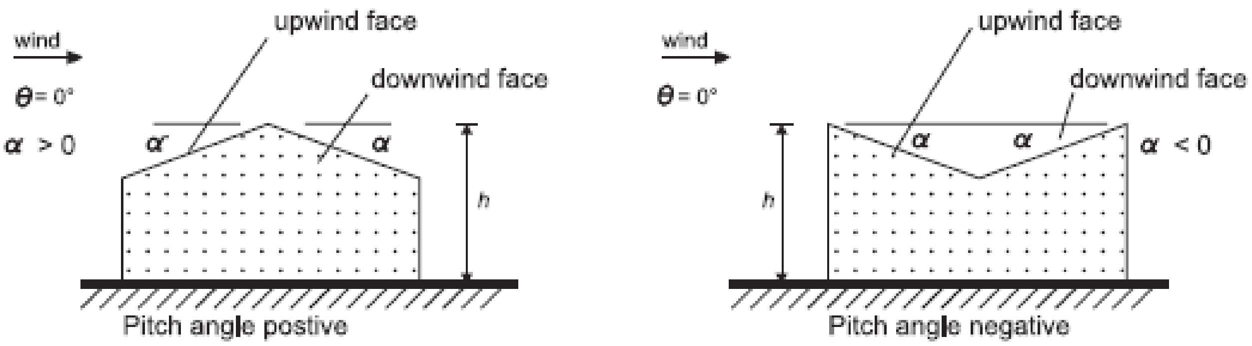
NOTE 1 At $\theta = 0°$ (see table a)) the pressure changes rapidly between positive and negative values around a pitch angle of $\alpha = +5°$ to $+45°$, so both positive and negative values are given. For those roofs, two cases should be considered: one with all positive values, and one with all negative values. No mixing of positive and negative values is allowed on the same face.

NOTE 2 Linear interpolation for intermediate pitch angles may be used between values of the same sign. The values equal to 0.0 are given for interpolation purposes

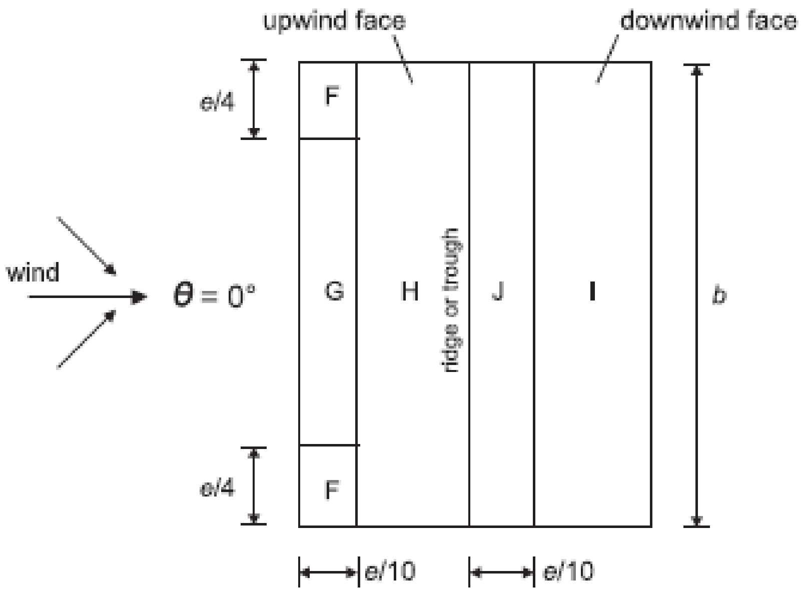
Appendix D11

Duopitch roofs

The roof, including protruding parts, should be divided into zones as shown in Figure below. The reference height z_e should be taken equal to h.



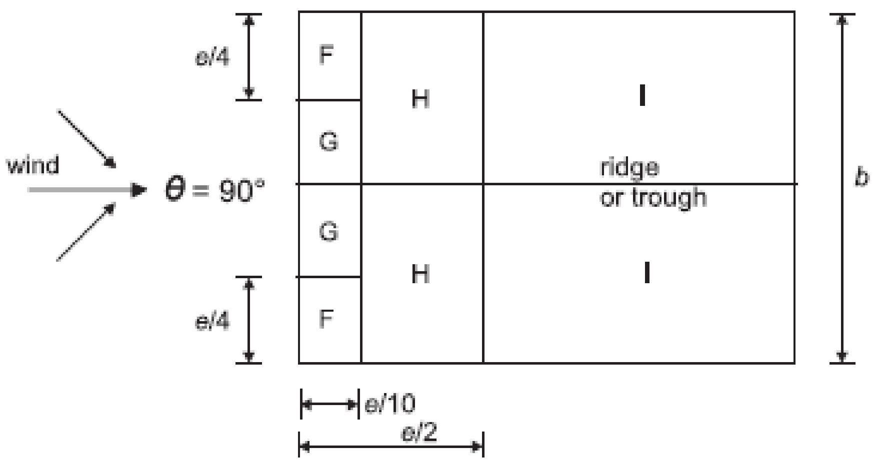
(a) general



$e = b$ or $2h$
whichever is smaller

(b) wind direction $\theta = 0°$

b : crosswind dimension



(c) wind direction $\theta = 90°$

Appendix D12

Duopitch roofs

Table 7.4a — External pressure coefficients for duopitch roofs

Pitch Angle α	Zone for wind direction $\theta = 0°$									
	F		G		H		I		J	
	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$
-45°	-0,6		-0,6		-0,8		-0,7		-1,0	-1,5
-30°	-1,1	-2,0	-0,8	-1,5	-0,8		-0,6		-0,8	-1,4
-15°	-2,5	-2,8	-1,3	-2,0	-0,9	-1,2	-0,5		-0,7	-1,2
-5°	-2,3	-2,5	-1,2	-2,0	-0,8	-1,2	+0,2		+0,2	
							-0,6		-0,6	
5°	-1,7	-2,5	-1,2	-2,0	-0,6	-1,2	-0,6		+0,2	
	+0,0		+0,0		+0,0				-0,6	
15°	-0,9	-2,0	-0,8	-1,5	-0,3		-0,4		-1,0	-1,5
	+0,2		+0,2		+0,2		+0,0		+0,0	+0,0
30°	-0,5	-1,5	-0,5	-1,5	-0,2		-0,4		-0,5	
	+0,7		+0,7		+0,4		+0,0		+0,0	
45°	-0,0		-0,0		-0,0		-0,2		-0,3	
	+0,7		+0,7		+0,6		+0,0		+0,0	
60°	+0,7		+0,7		+0,7		-0,2		-0,3	
75°	+0,8		+0,8		+0,8		-0,2		-0,3	

NOTE 1 At $\theta = 0°$ the pressure changes rapidly between positive and negative values on the windward face around a pitch angle of $\alpha = -5°$ to $+45°$, so both positive and negative values are given. For those roofs, four cases should be considered where the largest or smallest values of all areas F, G and H are combined with the largest or smallest values in areas I and J. No mixing of positive and negative values is allowed on the same face.

NOTE 2 Linear interpolation for intermediate pitch angles of the same sign may be used between values of the same sign. (Do not interpolate between $\alpha = +5°$ and $\alpha = -5°$, but use the data for flat roofs in 7.2.3). The values equal to 0,0 are given for interpolation purposes

Table 7.4b — External pressure coefficients for duopitch roofs

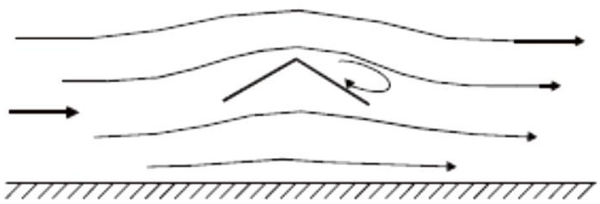
Pitch angle α	Zone for wind direction $\theta = 90°$							
	F		G		H		I	
	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$	$c_{pe,10}$	$c_{pe,1}$
-45°	-1,4	-2,0	-1,2	-2,0	-1,0	-1,3	-0,9	-1,2
-30°	-1,5	-2,1	-1,2	-2,0	-1,0	-1,3	-0,9	-1,2
-15°	-1,9	-2,5	-1,2	-2,0	-0,8	-1,2	-0,8	-1,2
-5°	-1,8	-2,5	-1,2	-2,0	-0,7	-1,2	-0,6	-1,2
5°	-1,6	-2,2	-1,3	-2,0	-0,7	-1,2	-0,6	
15°	-1,3	-2,0	-1,3	-2,0	-0,6	-1,2	-0,5	
30°	-1,1	-1,5	-1,4	-2,0	-0,8	-1,2	-0,5	
45°	-1,1	-1,5	-1,4	-2,0	-0,9	-1,2	-0,5	
60°	-1,1	-1,5	-1,2	-2,0	-0,8	-1,0	-0,5	
75°	-1,1	-1,5	-1,2	-2,0	-0,8	-1,0	-0,5	

Appendix D13 Canopy roof

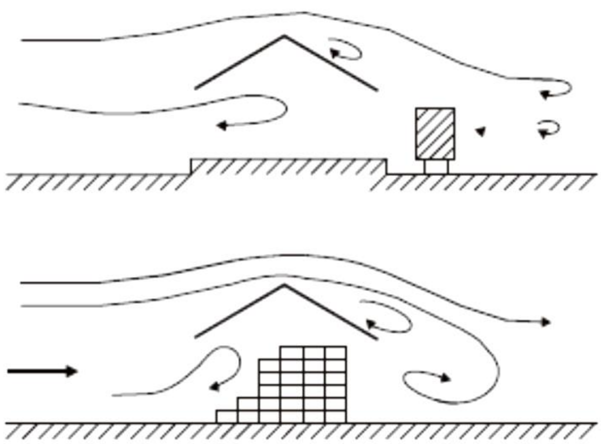
A canopy roof is defined as the roof of a structure that does not have permanent walls, such as petrol stations, dutch barns, etc.

The degree of blockage under a canopy roof is shown in Figure 7.15. It depends on the blockage φ, which is the ratio of the area of feasible, actual obstructions under the canopy divided by the cross sectional area under the canopy, both areas being normal to the wind direction. φ = 0 represents an empty canopy, and φ = 1 represents the canopy fully blocked with contents to the down wind eaves only (this is not a closed building).

The overall force coefficients, c_f, and net pressure coefficients $c_{p,net}$, given in Tables 7.6 to 7.8 for φ = 0 and φ = 1 take account of the combined effect of wind acting on both the upper and lower surfaces of the canopies for all wind directions. Intermediate values may be found by linear interpolation.



Empty, free-standing canopy (φ = 0)



Canopy blocked to the downwind eaves by stored goods (φ = 1)

Appendix D14 Duopitch canopy

Duopitch canopy (Table 7.7) the centre of pressure should be taken at the centre of each slope (Figure 7.17). In addition, a duopitch canopy should be able to support one pitch with the maximum or minimum load, the other pitch being unloaded.

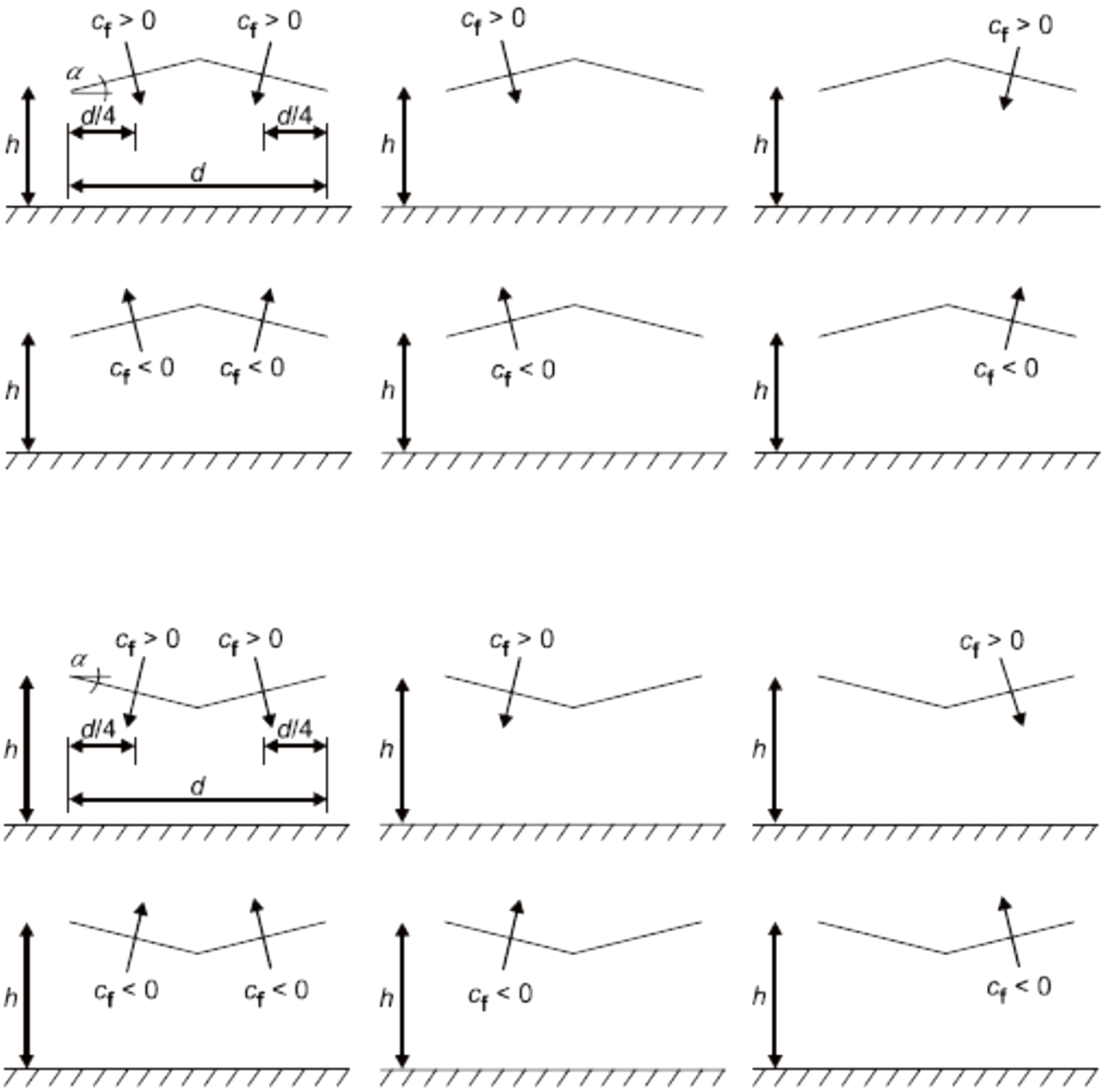


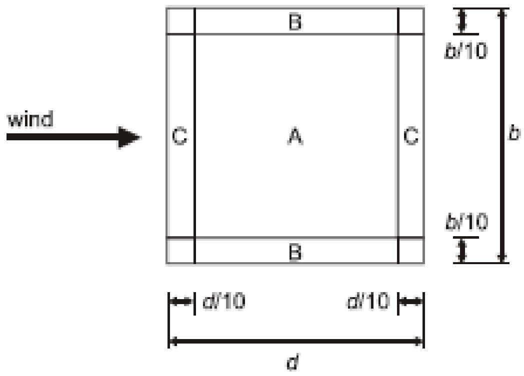
Figure 7.17 — Arrangements of loads obtained from force coefficients for duopitch canopies

Appendix D15

Table 7.6 — $c_{p,net}$ and c_f values for monopitch canopies

Net Pressure coefficients $c_{p,net}$

Key plan



Roof angle α	Blockage φ	Overall Force Coefficients c_f	Zone A	Zone B	Zone C
0°	Maximum all φ	+ 0,2	+ 0,5	+ 1,8	+ 1,1
	Minimum φ = 0	- 0,5	- 0,6	- 1,3	- 1,4
	Minimum φ = 1	- 1,3	- 1,5	- 1,8	- 2,2
5°	Maximum all φ	+ 0,4	+ 0,8	+ 2,1	+ 1,3
	Minimum φ = 0	- 0,7	- 1,1	- 1,7	- 1,8
	Minimum φ = 1	- 1,4	- 1,6	- 2,2	- 2,5
10°	Maximum all φ	+ 0,5	+ 1,2	+ 2,4	+ 1,6
	Minimum φ = 0	- 0,9	- 1,5	- 2,0	- 2,1
	Minimum φ = 1	- 1,4	- 2,1	- 2,6	- 2,7
15°	Maximum all φ	+ 0,7	+ 1,4	+ 2,7	+ 1,8
	Minimum φ = 0	- 1,1	- 1,8	- 2,4	- 2,5
	Minimum φ = 1	- 1,4	- 1,6	- 2,9	- 3,0
20°	Maximum all φ	+ 0,8	+ 1,7	+ 2,9	+ 2,1
	Minimum φ = 0	- 1,3	- 2,2	- 2,8	- 2,9
	Minimum φ = 1	- 1,4	- 1,6	- 2,9	- 3,0
25°	Maximum all φ	+ 1,0	+ 2,0	+ 3,1	+ 2,3
	Minimum φ = 0	- 1,6	- 2,6	- 3,2	- 3,2
	Minimum φ = 1	- 1,4	- 1,5	- 2,5	- 2,8
30°	Maximum all φ	+ 1,2	+ 2,2	+ 3,2	+ 2,4
	Minimum φ = 0	- 1,8	- 3,0	- 3,8	- 3,6
	Minimum φ = 1	- 1,4	- 1,5	- 2,2	- 2,7

NOTE + values indicate a net downward acting wind action

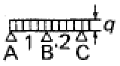
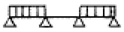
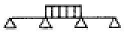
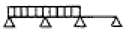
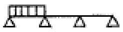
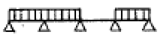
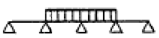
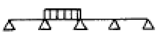
- values represent a net upward acting wind action

+ values indicate a net downward acting wind action;
- values represent a net upward acting wind action

Appendix E1: Continuous beams with uniformly-distributed loads Sectional forces

load case	max. field moment (factor: qL^2)					support moment (factor: qL^2)				reaction forces (factor: qL)				
	M_1	M_2	M_3	M_4	M_5	M_B	M_C	M_D	M_E	A	B_v B_h	C_v C_h	D_v D_h	E_v E_h
2 spans A 1 B 2 C, q	0,0703	0,0703				−0,1250				0,3750	0,6250 0,6250	0,3750		
L v L v	0,0957					−0,0625				0,4375	0,5625 0,0625	−0,0625		
3 spans A 1 B 2 C 3 D	0,0800	0,0250	0,0800			−0,1000	−0,1000			0,4000	0,6000 0,5000	0,5000 0,6000	0,4000	
	0,1013		0,1013			−0,0500	−0,0500			0,4500	0,5500 0	0 0,5500	0,4500	
		0,0750				−0,0500	−0,0500			−0,0500	0,0500 0,5000	0,5000 0,0500	−0,0500	
	0,0735	0,0535				−0,1167	−0,0333			0,3833	0,6167 0,5834	0,4166 0,0333	−0,0333	
	0,0939					−0,0667	+0,0167			0,4333	0,5667 0,0834	−0,0834 −0,0167	0,0167	
4 spans A 1 B 2 C 3 D 4 E	0,0772	0,0364	0,0364	0,0772		−0,1071	−0,0714	−0,1071		0,3929	0,6071 0,5357	0,4643 0,4643	0,5357 0,6071	0,3929
	0,0996		0,0805			−0,0536	−0,0357	−0,0536		0,4464	0,5536 0,0179	−0,0179 0,4821	0,5179 0,0536	−0,0536
	0,0720	0,0610		0,0977		−0,1205	−0,0179	−0,0580		0,3795	0,6205 0,6026	0,3974 −0,0401	0,0401 0,5580	0,4420
		0,0561	0,0561			−0,0357	−0,1072	−0,0357		−0,0357	0,0357 0,4285	0,5715 0,5715	0,4285 0,0357	−0,0357
	0,0940					−0,0665	+0,0179	−0,0045		0,4335	0,5665 0,0844	−0,0844 −0,0224	0,0224 0,0045	−0,0045
		0,0737				−0,0491	−0,0536	+0,0134		−0,0491	0,0491 0,4955	0,5045 0,0670	−0,0670 −0,0134	0,0134

Appendix E2: Continuous beams with uniformly-distributed loads Deflection

load case	deflection in mid span $w = k \dfrac{qL^4}{100EI}$			
	k_1	k_2	k_3	k_4
2 spans 	0,521	0,521		
	0,912	−0,391		
3 spans 	0,677	0,052	0,677	
	0,990	−0,625	0,990	
	−0,313	0,677	−0,313	
	0,573	0,365	−0,208	
	0,885	−0,313	0,104	
4 spans 	0,632	0,186	0,186	0,632
	0,967	−0,558	0,744	−0,355
	0,549	0,437	−0,474	0,939
	−0,223	0,409	0,409	−0,223
	0,884	−0,307	0,084	−0,028
	−0,307	0,660	−0,251	0,084

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