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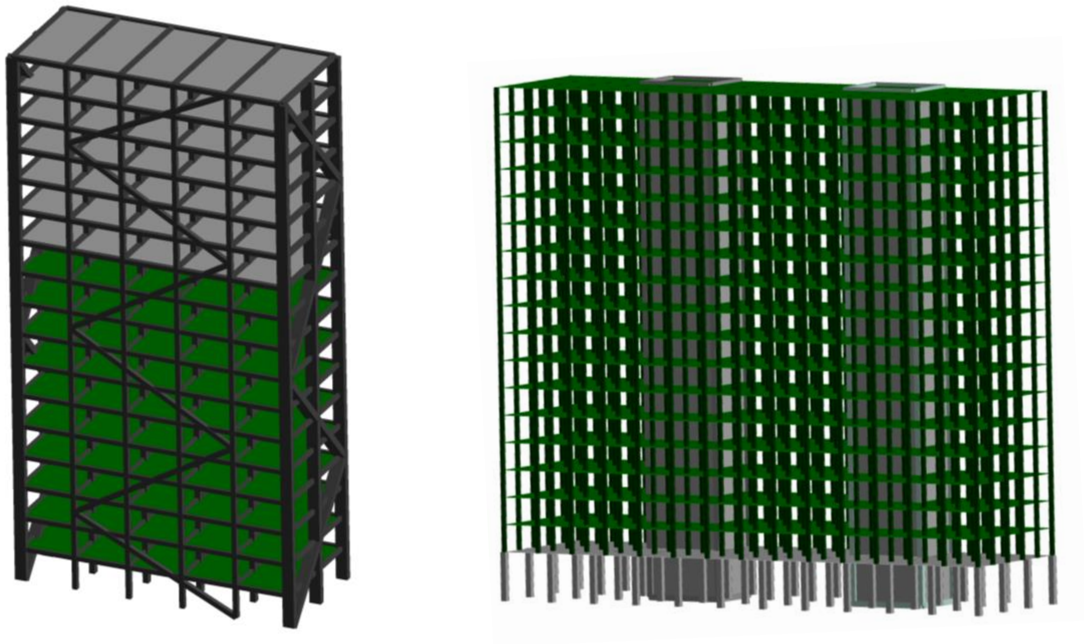

Design of Tall Timber Buildings in Scandinavia and Canada – A Comparison Study

Master's thesis in Structural Engineering and Building Technology

OSKAR OLSSON

Department of Architecture and Civil Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
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Master's Thesis 2022

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Cover: Models of Mjøstårnet and Brock Commons created in *ANSYS*

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ABSTRACT

Scandinavia and Canada are two places with many forests and benefit from the sustainable change where timber is becoming more and more relevant, even when designing tall buildings where steel and concrete have been and still are the dominant material to use. This thesis compares the building and design practices for tall timber buildings in Scandinavia and Canada. This will be done in three parts. Firstly will be a literature study to understand the main design criteria for designing tall timber buildings and how it differs between the two places. Secondly, a questionnaire where experts in Scandinavia and Canada are asked about their thoughts on the design process of tall timber buildings. Lastly, two models will be created using the program *ANSYS*, one representing Mjøstårnet and one representing Brock Commons. These models will be analyzed to understand better how a timber design from Scandinavia differs from one in Canada, especially regarding the seismic load, which is not considered in Scandinavia. The results from these parts are that the design process for tall timber buildings is similar in Scandinavia and Canada but with some differences, especially regarding fire design, where Canada is more conservative than Scandinavia, and seismic design, which is not considered in Scandinavia. The computer models show that having a hybrid solution like Brock Commons creates a better design than the all timber solution found in Mjøstårnet and how the lateral load like wind and seismic becomes an obstacle for tall timber buildings. Therefore, a hybrid solution is an excellent solution to make the design easier to comply with codes and regulations. Some results indicate that having a total timber solution like Mjøstårnet could be a possible seismic design for a tall timber building, but it would need to have a different shape than Mjøstårnet.

Keywords: Timber engineering, structural systems, tall timber buildings, fire design, seismic design, frequency analysis

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Preface

This thesis marks the end of a five-year study period at the Chalmers University of Technology, resulting in a bachelor's degree in Civil and Environmental Engineering and a master's in Structural Engineering and Building Technology. The thesis was carried out as a collaboration between the Division of Structural Engineering at the Chalmers University of Technology and the Faculty of Forestry at the University of British Columbia.

I have many people to thank for sharing their knowledge and help throughout my thesis journey. A big thanks go to my supervisor Cristiano Loss, Assistant Professor at the University of British Columbia, who both made me feel welcome at the University of British Columbia and was able to share his expertise when it comes to timber structures. I also would like to pay special thanks to my supervisor and examiner, Robert Jockwer, Assistant Professor at the Chalmers University of Technology, for his never-ending support and stream of knowledge. I also want to thank David Owolabi, a Ph.D. graduate student at UBC, who was immensely helpful when it came to computer modeling and was always keen to have a discussion.

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Finally, I want to thank my family and loved ones who have supported me throughout my academic journey. It is because of their support that I am where I am today.

Gothenburg June 2022

Oskar Olsson

1 Introduction

Building sustainably, environmentally, and socially is the new norm in the building sector, and with this norm, the popularity of timber increased. Timber is more environmentally friendly than concrete and steel, which are common building materials. Tall buildings have also risen in popularity since the need to create dense cities arose. Steel and concrete are still dominant as structural materials when building tall buildings, but timber is becoming more frequent even there. A simple comparison to why steel and concrete have been more used for tall buildings is to compare the tallest building in the world with the tallest timber building. The tallest building in the world is Burj Khalifa, and it reaches 828 meters up in the sky, while Mjøstårnet, which is considered the tallest timber building in the world, only reaches 85.4 meters up in the sky, just a bit over a tenth of the height of Burj Khalifa.

A timber building as tall as Burh Khalifa will likely not happen anytime soon. However, with new research on timber, can the design criteria and codes for timber buildings change to be used more frequently, which would help the journey of becoming more sustainable.

1.1 Background

Scandinavia and Canada are two places that are similar geographically. They are both in the north, have various weather, and have many forests. The significant amount of forest makes these two areas extra advantageous to use timber as a building material.

Even though Scandinavia and Canada have similarities, there are differences in the design process of tall timber buildings. An example would be how high it is allowed to build with timber. According to the Swedish National Board of Housing (Boverket, n.d.), there is no restriction on how high timber buildings can be. Whereas in Canada, there is a limit to 12 stories. The difference in regulation means that timber buildings located in Scandinavia might not be suitable for Canada or even allowed there. By comparing these two building practices, would it be possible to find areas where they are different and study what they can learn from each other. It would also make it easier to use materials and designs and know what needs to be changed to fit the new building practice and regulations.

The benefits of using timber as a material in buildings are many. Some of these benefits are the fast construction phase because of the lightness of timber, environmental superiority compared to steel and concrete, and its excellent strength-to-weight ratio.

1.2 Aim

This thesis aims to compare the design process for tall timber buildings in Scandinavia and Canada. The comparison will be made by comparing the different codes and building practices for the two areas. Furthermore, an analysis of how the design criteria in Scandinavia and Canada can learn from each other will be performed and what areas are more challenging in the design process in these two places.

Another aim is to understand how the limitations of tall timber buildings differ between Scandinavia and Canada. Finally, an analysis will be done to understand better the possibility of using pure timber buildings or if it is better to use a hybrid solution.

1.3 Objectives

A literature study will be performed to answer the following questions:

- What are the main design criteria when designing tall timber buildings?
- How does the building practice differ between Scandinavia and Canada?
- How do the design criteria differ between Scandinavia and Canada?
- Do the timber products used in Scandinavia differ from those used in Canada?

A questionnaire will be sent out to working professionals in Scandinavia and Canada to answer the following questions:

- Is there an upgoing trend for tall timber buildings?
- What are the main obstacles when it comes to designing tall timber buildings?
- Are there any parts of the design code/building practice for designing tall timber buildings that are easier to understand?
- Are there any parts of the design code/building practice for designing tall timber buildings that are harder to understand?

A computer modeling of a reference project will be used to answer the following questions:

- What are the limitations of using pure timber buildings, and how does that differ between Scandinavia and Canada?
- Which part of the design process for tall timber buildings is the most critical in Scandinavia and Canada?
- How would a tall timber building differ if it was built in Scandinavia versus Canada?

1.4 Limitations

Vancouver and the province of British Columbia will be used as a reference point when looking at the design process of tall timber buildings in Canada. This is because different provinces in Canada have various regulations and design criteria. The seismic activity in Vancouver is also something that differs a lot compared to Scandinavia. The Swedish building code and practice will be used to represent Scandinavia.

Because of time limitations, this study will not detail every aspect of how timber buildings are designed. Connections, for example, are an essential and challenging aspect of building timber buildings and will not be looked at in detail.

For the computer modeling, simplifications will be made for connections, boundary conditions, and the geometry for the reference building. Simplification is necessary to save time and to be able to model a complex structure with more ease.

1.5 Method

The process of this thesis was divided into three parts: a literature study, a questionnaire, and computer modeling.

The literature study was performed to understand the design process of tall timber buildings in both Scandinavia and Canada. The study gave a good understanding of materials and systems used when building tall timber buildings and the design difficulties of using timber.

A questionnaire was put together regarding the design process of tall timber buildings. This questionnaire was then used to get the thoughts and opinions of working professionals in the timber engineering field.

A simplified version of Mjøstårnet and Brock Commons was modeled in the program *ANSYS*. These models were analyzed with the following analyses:

- Frequency analysis
- Lateral load analysis
- Vibration analysis
- Response spectrum analysis

These analyses aim to understand better the differences between using a pure timber system with a hybrid one and how well a design from Scandinavia would work in Canada, where they have different regulations and seismic loads to consider.

2 Mass Timber Products

Timber buildings have traditionally been made of light-frame construction. A light-frame construction is dimensional lumber and engineering wood fastened together with nails to create floor, walls, stairs, and roof assemblies (Naturally:wood, 2022). Light frame construction is widely used for family or multifamily homes, but more was needed if timber would be used for taller buildings. The development of mass timber started in Austria (Gustavsson, et al., 2019) when something called cross-laminated timber (CLT) was invented in the 1990s. Mass timber products are typically formed through lamination, fasteners, or adhesives. Since the 1990s, various products have been developed and are currently used when designing tall timber buildings.

A building made of mass timber can have a robust structural system that uses large, solid wood panels, columns, or beams (Naturally:wood, 2022). With structural systems made up of these newer mass timber products have taller timber buildings been made possible. Some of the most common mass timber products used in tall timber buildings are as follows:

- Cross-laminated timber
- Glued laminated timber
- Laminated veneer lumber

These products have in common that they are made of pieces of wood glued together in different ways and formations. With this method, can the orthotropic property of wood become neglectable by placing the wood glued together at an angle, as used in creating CLT. In addition, discrepancies like knots that can worsen the structural capacity are also a lesser risk for these materials.

2.1 Cross-Laminated Timber

Cross-laminated timber (CLT) consists of boards (or laminates) made of timber glued together where each layer is placed at an angle of 90 degrees to the next, see Figure 2.1. A CLT consists of at least three layers of boards, but more layers can be added depending on its purpose. There are many areas of usage for CLT where some of the most prominent are floors and walls. In addition, the high load-bearing capacity and stiffness make CLT panels helpful in taking care of loads and stabilizing the structure (Gustavsson, et al., 2019).

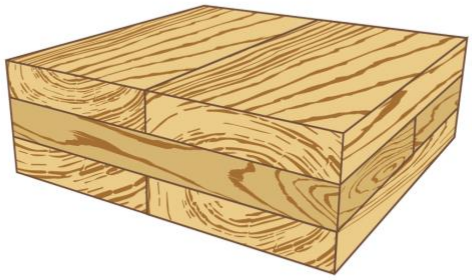


Figure 2.1 Image of cross-laminated timber (Naturally:wood, 2022). Reprinted with permission.

2.2 Glued Laminated Timber

Glued laminated timber (Glulam) consists of laminates stacked and glued together without changing the direction of the wood, see Figure 2.2. This increases the average strength of the product compared to regular timber, where there is no lamination (Gross, 2016). Glulam is usually used as posts and beams to hold up the structural system. It is also possible to bend glulam to create curves for beams or trusses. Beautiful structural systems can be designed with visible glulam.

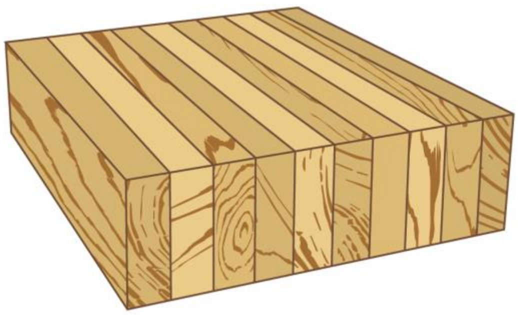


Figure 2.2 Image of glued laminated timber (Naturally:wood, 2022). Reprinted with permission.

2.3 Laminated Veneer Lumber

Laminated veneer lumber (LVL) consists of thin veneer sheets bonded with adhesives to create large blocks. The use of thin veneer sheets reduces the effect of inconsistencies in the timber. When put together into one large block, is it high strength with relatively low mechanical variation compared to other products that glue larger timber specimens together. LVL is used as beams, trusses, planks, and rafters. It can also form the load-bearing floor and wall panels, but then it should be cross bonded to increase stiffness (Naturally:wood, 2022).

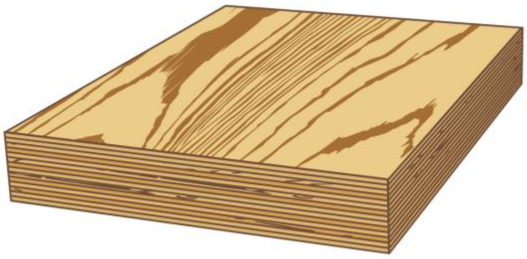


Figure 2.3 Image of laminated veneer lumber (Naturally:wood, 2022). Reprinted with permission.

2.4 Other Mass Timber Products

Other than CLT, glulam and LVL are there other mass timber products worth mentioning. These are as follows:

- Dowel laminated timber (DLT): Stacking lumber on its edge or cross laminating with dowels. This is the only mass timber product made without metal fasteners or adhesives.
- Nail laminated timber (NLT): Stacking lumber on its edge and fastening it with nails or screws.
- Mass plywood panel (MPP): Layers of wood veneer glued and pressed together. It can be used as large platforms, beams, or columns.
- Laminated Strand Lumber (LSL): Thin strands of wood are aligned parallel to the length of the member and glued together.
- Parallel strand lumber (PSL): Created by long strands of clipped veneers that are laid in a parallel formation and then bonded with an adhesive. Very similar to LSL, but with the PSL is the length-to-thickness ratio higher.

2.5 Hybrid Material

Some of the benefits of using timber are that it is very light compared to its strength, easy to transport, and fast when it comes to construction. However, using timber also has its disadvantages. Its lack of mass can become a problem regarding stability, and the acoustic performance is bad (StructureCraft, n.d.). Therefore, it is helpful to use timber-steel or timber-concrete composites where each material is used best.

2.5.1 Timber - Steel Composite

Timber-steel composite beams are one example of how steel adds beneficial material properties to the structural element made of timber. The steel increases the load-bearing capacity and stiffness while still being considerably light and easy to handle because of the timber (Chybiniski, Polus, Szwabinski, & Niewiem, 2019).

Steel is also used in the connection between timber elements. This is because of steel's high load-bearing strength, flexibility in shape, and homogeneous properties. As a result, steel connectors can be everything from just a steel plate to more complex ones. An example can be found in Figure 2.4.

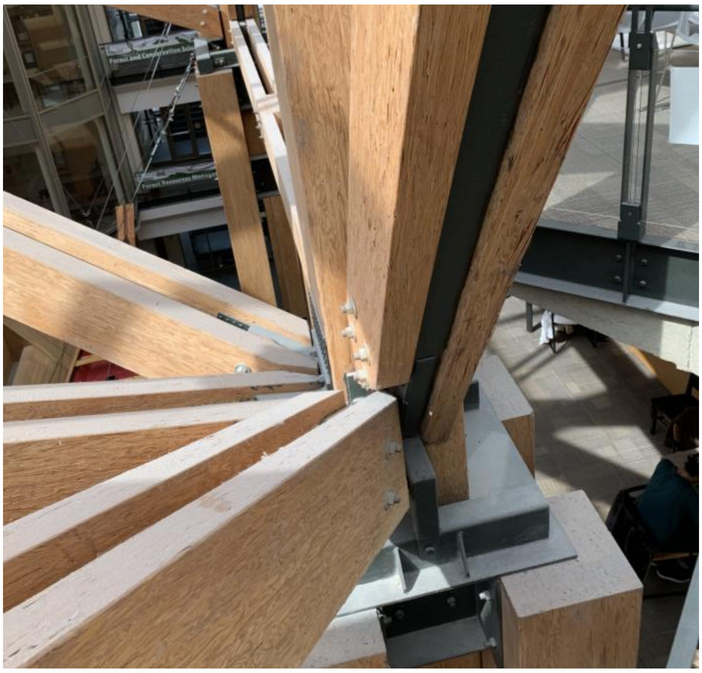


Figure 2.4 Complex steel connection between timber elements.

2.5.2 Timber - Concrete Composite

A typical timber-concrete composite is to have a layer of concrete on top of mass timber panels like CLT or DLT that is used for floors, see Figure 2.6. Hybridization aims to enable designers to increase spans, reduce deflection, and improve vibration performance (StructureCraft). The added concrete on top of timber is also beneficial for tall timber buildings because it adds mass to the structure, which helps with the stabilization.

The timber and concrete must be well connected to create a working composite action. A standard connection is mechanical fasteners, but adhesives are used in some cases. Without fasteners, would the two materials slide on top of each other and not serve their purpose. The best use of concrete would be to have it in compression while the timber takes care of the tensile stresses (Lukaszewska, 2009).

Figure 2.5 Image of a timber-concrete composite (StructureCraft). Reprinted with permission.

3 Tall timber buildings

Scandinavia and Canada are places where some of the tallest and most impressive timber buildings exist. Some of these buildings have been ground-breaking projects that have pushed the limit of tall timber buildings. For example, Mjøstårnet in Norway pushed the highest height of tall timber buildings up to 85.4 meters. This chapter will include some of the most common timber structural systems, what kind of structural systems the market offer, and some of the tallest timber buildings in Scandinavia and Canada.

3.1 Structural systems

The structural system is the base of any building to transfer loads to the ground. Using a structural system made out of timber to support a tall building is still pretty new, but new concepts and prototypes have been developed in the last couple of years. Nevertheless, in general, can the following structural systems be created by using mass timber products (Kesik & Martin, 2021):

- Post and beam: Posts and beams are used to create a framework that supports wood floor and roof panels made of laminated timber. The advantage of using this system is that the products used can be retrieved from several different suppliers. A downside is that it is not quite as time-efficient as some other systems because of many members and connectors.
- Post and platform: This approach is both time and cost-effective, but with the downside that it does not provide sufficient lateral resistance on its own. Another disadvantage is that the post and platform system is proprietary and unique depending on the supplier. However, this also means that the supplier can provide design assistance to the project team.
- Mass timber panels: This system uses CLT as its primary building material for structural wall and roof elements. Glulam beams and columns can also be integrated to achieve different architectural needs. A downside of using this structural system for tall buildings is that the higher the building is, the harder it is to withstand the lateral loads. New methods connect the shear walls and floor diaphragms to gravity load-bearing elements to provide a more efficient lateral load resistance. The advantage of using mass timber panels is the flexibility in design, but a disadvantage is that it is harder to fulfill the fire and acoustics requirements.
- Braced mass timber: The braced mass timber system is a variation of the post and beam system with the difference that diagonal bracing to create a system that can resist the lateral loads. This removes the need for shear walls and elevator/stair shafts to provide the lateral loads.
- Module system: A somewhat unconventional structural system that uses prefabricated modules stacked on top of each other. This creates an excellent load-bearing capacity, a stable and precise structure, high technical performance, and a layout where it is easy to make openings. However, a disadvantage is that it is not as flexible as the other systems (Stora Enso, 2016).

3.2 Systems on the market

With tall timber buildings being relatively new to the market, have several concepts and building systems in recent years been developed by companies to give a more detailed view of how a possible timber building can look. In addition, these concepts and systems provide a clear view of how structural systems will carry the load and handle conflicts that come with using timber. In this chapter are some of the concepts presented.

3.2.1 Trä8

Moelven is a big business group located in Sweden and Norway and does everything from manufacturing and producing timber products. They also develop building systems that can be used when designing timber buildings, one of which is a glulam beams and columns system called Trä8 (Moelven, 2022), see Figure 3.1. Trä8 is designed to use the least amount of material possible to promote sustainability. It can have a free span of up to 8 meters, making it flexible for designing commercial buildings or living spaces. Moelven also offers to make the elevator shafts and staircases in CLT. They say that keeping those parts in prefabricated concrete is more common to stabilize the building against lateral loads. According to Moelven can Trä8 be used to create a design that complies with sound, vibration, and fire requirements.

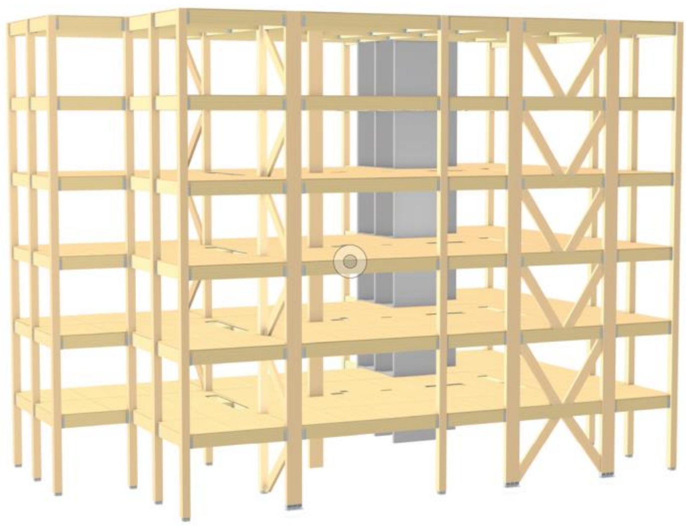


Figure 3.1 Model of a Trä8 system (Moelven, 2022). Reprinted with permission.

3.2.2 FFTT

FFTT stands for: Finding the Forest Through the Trees and is a tilt-up structural system created by two Canadians, Michael Green and Eric Karsh (2012). This system consists of mass timber panels tilted up like balloon frame walls, columns, a central core with either wood or embedded steel ledger, and beams that receive the wood floor slabs. Michael green and Eric Karsh have conceptualized FFTT to a height of 30 stories for a building located in a high seismic area like Vancouver. Steel beams and ledger beams would be needed to be integrated with the mass timber panels if this system would be used for a building over 12 stories.

Further research might be needed when building tall, but some guidelines need more attention when building high using the FFTT system. For example, see the following recommendations for 20- and 30-story buildings (Karacabeyli & Lum, 2014).

20-story building (under 60 m high)

- Foundation should be designed to resist overturning, as overturning will most likely govern the design.
- Vibrations due to wind loads will typically govern the design, even in seismic zones.
- The FFTT can be used by using a structural core and additional shear walls that are linked with steel beams.

30-story building (100 m high)

- Extensive testing and analysis may be required.
- Vibrations due to wind will most likely be the governing factor.
- The FFTT system can be used but would require a structural core, additional shear walls, and steel link beams.

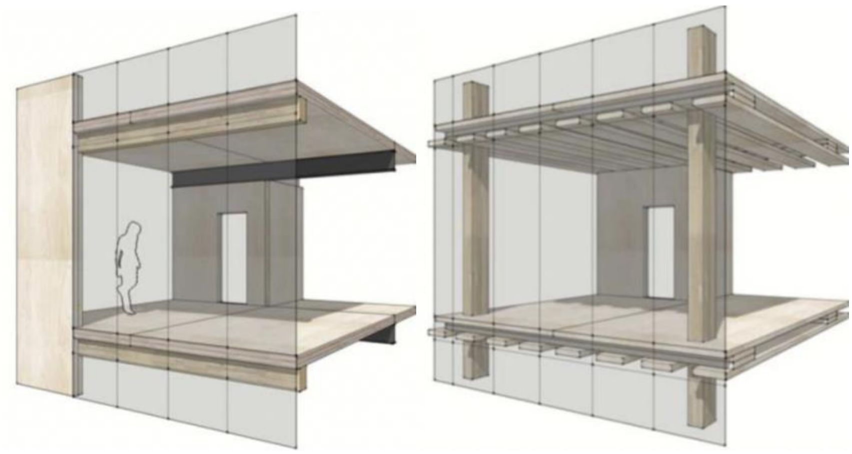


Figure 3.2 Examples of how the FFTT system can be configurated to fit different facades. (Michael Green Architecture, 2014). Republished with permission.

3.2.3 CJTF

A concrete jointed timber frame (CJTF) system by SOM, American architecture and engineering firm, was proposed in 2013 for a new 42-story timber-composite high-rise (Karacabeyli & Lum, 2014). As the name entails, this system uses mass timber for the main structural elements and introduces reinforced concrete at the joints. The concrete at the joints eliminates the cumulative deformation that can occur due to compression perpendicular to the grain in the timber. A reinforced concrete beam is used as the perimeter beam. With the help of rebar are the timber panels connected to each other and the concrete. The lateral load is taken care of shear walls made of CLT or other solid timber panels. With the foundation and first level being made out of concrete and the other concrete elements mentioned earlier, the structure comprises approximately 30% concrete and 70% timber.

Like the FFTT system, some guidelines were provided for tall buildings when using the CJTF system. For example, see the following recommendations for 20- and 30-story buildings (Karacabeyli & Lum, 2014).

20-story building (under 60 m high)

- Foundation should be designed to resist overturning, as overturning will most likely govern the design.
- Vibrations due to wind loads will typically govern the design, even in seismic zones.
- To reduce the building period and the uplift of a structure using the CJTF system, can link beams between walls be used, but it is not strictly required.

30-story building (100 m high)

- Extensive testing and analysis may be required.
- Vibrations due to wind will most likely be the governing factor.
- Link beams between walls are required.

3.2.4 CEI Architecture

CEI Architecture is a Canadian firm that together with the structural engineering firm Read Jones Christoffersen developed a proposal for a 40-story timber-concrete hybrid building. The concept consists of a concrete core, wood-concrete hybrid floor panels with a span of up to 9 meters, mass timber trusses at the building parameter on every second floor, and chords supporting the hybrid floor panels. The concrete of the building provides support for the lateral loads, while the timber elements provide gravity support at each level (Green, 2012).

3.2.5 LCT

CREE is an international construction collective from Austria that creates building solutions. They have created a timber-concrete hybrid concept called LifeCycle Tower (LCT). The LCT system creates a potential height of 30 stories and can have floor spans of up to 9.4 meters. The system uses glulam beams and columns as the primary building material and prefabricated concrete-timber composite deck elements. The connection between the deck and the glulam columns is achieved with a mortise joint forming a frame. Wood panels can be used for the core, but concrete and steel are also options. Furthermore, the LCT system has no structural dividing walls to enable maximum flexibility (Karacabeyli & Lum, 2014).

3.2.6 Stora Enso

Stora Enso is a big Finnish-Swedish company that produces anything wood-related. This can be anything from pulp and paper to laminated structural elements. Stora Enso also offers various building concepts for building with timber. For example, there are three concepts for tall buildings in timber for multi-story residential buildings and one for offices (Stora Enso, n.d.).

Multi-story residential

- CLT massive wood frame where the floors, internal walls, and envelope are framed, creating a robust system.

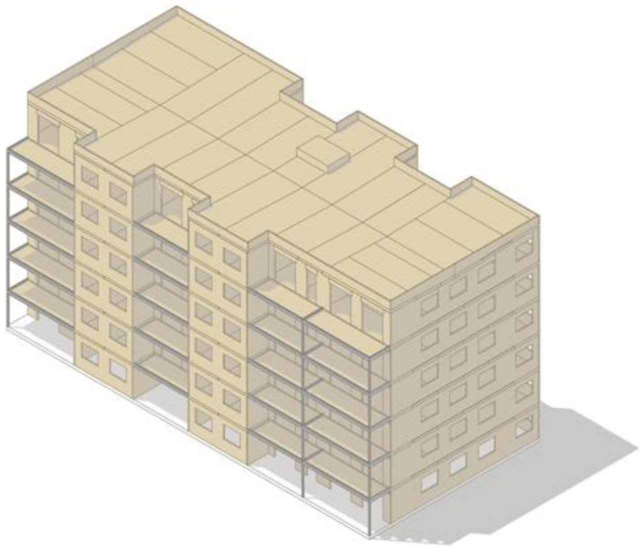


Figure 3.3 Structural system using CLT massive wood frame (Stora Enso). Republished with permission.

- CLT rib and timber frame, where inner walls and floors are framed with timber frame envelope. This is to increase the prefabrication level of external walls, internal space, and material use.

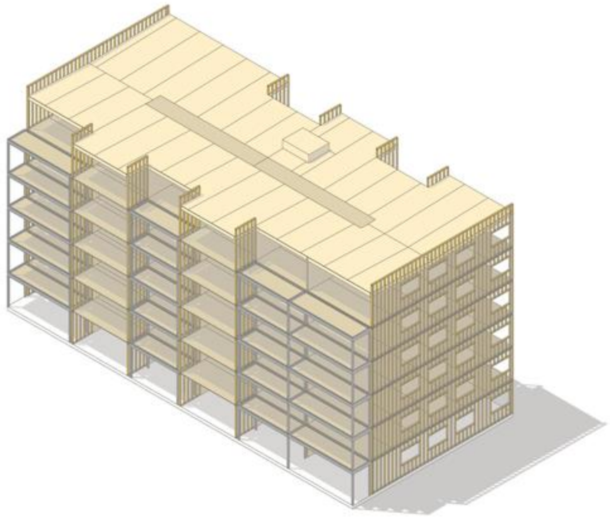


Figure 3.4 Structural system using CLT rib and timber frame (Stora Enso). Republished with permission.

- Beam and column systems are used to increase the flexibility and adaptability of the building depending on the layout and future needs.

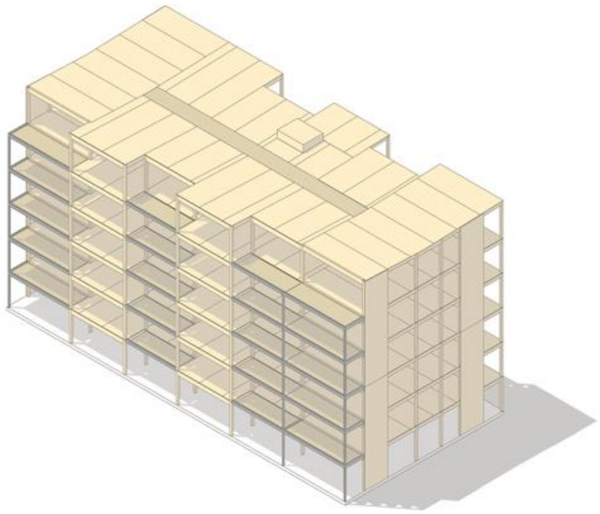


Figure 3.5 Structural system using timber beams and columns (Stora Enso). Republished with permission.

Office building

- A seven-story building with a floorplan shaped like an L that uses a CLT or LVL core as stabilization. The load is transferred through a beam and column system.

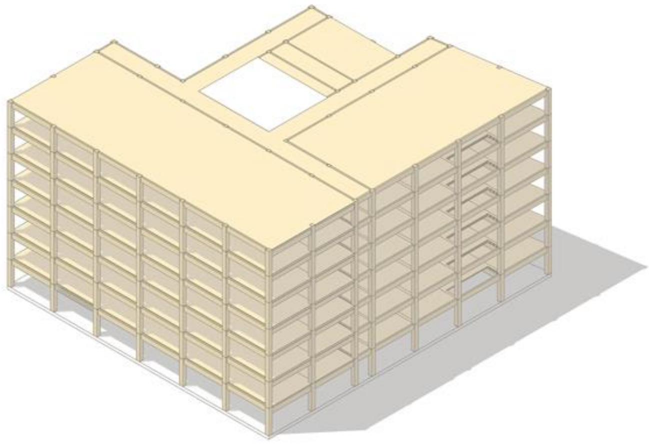


Figure 3.6 Structural system using a core of massive timber (CLT or LVL) and timber beams and columns (Stora Enso). Republished with permission.

These concepts also come with many technical reports regarding building physics, soundproofing, construction, materials that can be used, cost, and environmental studies, which gives a comprehensive and informative view of Stora Enso's concepts.

Stora Enso also has a comprehensive modular structural system that can be used for three to eight-story buildings. This modular system can be used in various variations and have many benefits. The most prominent ones are the ease of creating an easy and safe design, high-quality architecture and interior, and easy construction for the contractor (Stora Enso, 2016).

3.3 Timber Projects in Scandinavia and Canada

As mentioned earlier, both Scandinavia and Canada are places where several tall timber buildings have been built. These buildings have different uses, and timber has been used in different ways to create spectacular buildings. Following are some of the most famous and impressive structures built in Scandinavia and Canada.

3.3.1 Mjøstårnet

Mjøstårnet is an 18-story building located in Brumunddal, Norway, and is the tallest timber building globally. In this 11 200 m^2 building is a restaurant, hotel, offices, and apartments located. The groundwork started in 2017 and was completed and opened in 2019.

The structural system for Mjøstårnet is based on Moelven's Trä8 concept and consists of large glulam trusses along the facades and internal columns and beams. The trusses take the horizontal loads and give the building stiffness. In addition, a secondary load-bearing system is created with CLT walls for elevators and staircases. Prefabricated wooden decks are used for the second to the eleventh floor of Mjøstårnet. The floor above these uses concrete as floors to create a heavier and more stabilized building. In addition, the concrete floors help with the comfort criteria that are hard to comply with because of the building's slenderness and height.

The fire design for Mjøstårnet states that the main load-bearing system must be designed to withstand 120 minutes of fire, whereas the secondary load bearing needs to withstand 90 minutes of fire. The amount of charring was calculated for 120 minutes. The structural members were designed accordingly to have a significant enough cross-section to be still able to carry the loads during a fire. Fire retardant paint was used on visible wood elements in escape routes and internal walls in the main staircase and elevators. The CLT in the escape staircase was also covered with plasterboard to create an even better fire design. Glulam columns were tested with burnout tests to strengthen the credibility of the fire design (Abrahamsen R. , 2018).

On top of designing the structural elements in Mjøstårnet according to the fire requirement is the building also designed with fire sprinklers, firestops in the facades, steel connectors dowelled deep into the timber, and gaps between beams, columns, and plates will be fitted with an intumescent fire strip (Abrahamsen R. , 2018).

The report from Abrahamsen (2018) also talks about the dynamic design performed on Mjøstårnet to ensure a safe and comfortable design. Because of the low weight of the building from using timber, it is important to consider accelerations in the building to avoid motions that can cause discomfort, for example, nausea. The peak acceleration was calculated, and the conclusion was that the two highest floors of Mjøstårnet are on the limit level and even slightly above it. It is also stated that the effect caused by vibrations from wind loads will most probably be insignificant. A structural damping ratio of 1.9 % was used for the dynamic design, and no seismic loads were considered. The wind load was loaded as a static load, and no wind tunnel tests were performed because it was not necessary because of the Mjøstårnet's geometry.

Figure 3.7 Mjøstårnet during construction in 2018.

3.3.2 Sara Kulturhus

Sara Kulturhus is a building in Skellefteå, Sweden, finished in fall 2021. The building will act as a cultural center and hotel for the city. This tall timber structure that reaches around 80 meters into the air is built of glulam and CLT. CLT is used to create a structural core around the elevators and staircases. Modules made of CLT are stacked on top of each other to create rooms that the hotel will use. The modules are placed on top of glulam pillars in each corner which transfers the vertical loads, and the roof of the modules are interconnecting and transfers the load out to the CLT cores. Concrete floors are used instead of timber on floors 5-6 to dampen the noise from fans. Concrete was also used on floors 19 and 20 (and the roof) to give added weight and reduce the effect of wind (Sara Kultuhus, n.d.).

Sara Kulturhus has open timber elements that are only treated with a flame-retardant varnish (Sara Kulturhus, n.d.) and a sprinkler system with an added battery-driven pump as an added security (Fahlander, 2020).

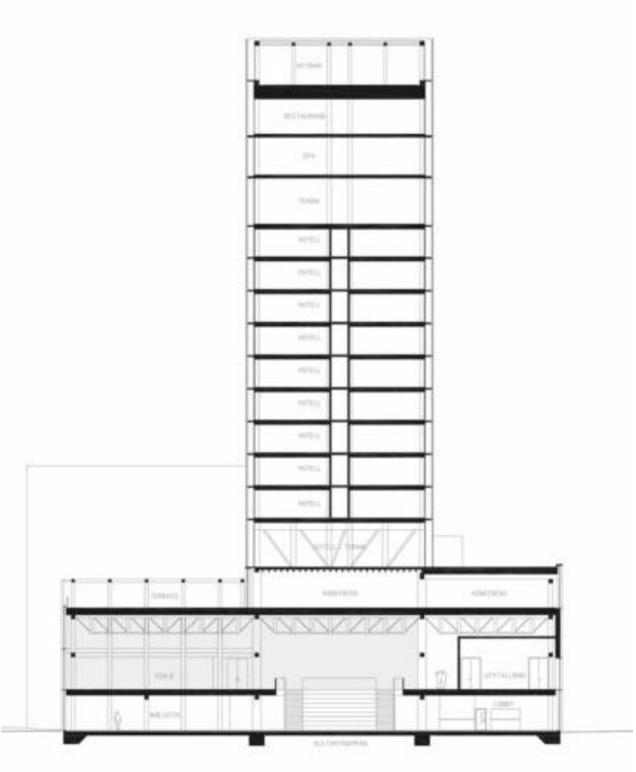


Figure 3.8 Section of Sara Kulturhus showing the structural members. (White Architects). Republished with permission.

3.3.3 Treet

Treet is a 14-story residential building that is located in Bergen, Norway. The structure consists of a glulam timber framework, balconies, a staircase in CLT, and prefabricated modules stacked on top of each other. Because of the building's location close to water, could the modules be delivered by ship, making it possible to use wider modules that would otherwise not be possible with transport on land. All the modules are independent units with their own insulation and weatherproofing, which was crucial during the assembly phase because of the rainy and humid climate in Bergen. The glulam frames were used to provide a platform between the stack of modules and the gap between modules. Framed and cladding are filled with insulation to help with the acoustics and fire measurements. All the structural elements are made of timber, and only the connections use slotted-in steel plates and dowels (UrbanNext, 2021). Treet used Moelven's Trä8 system, and when completed, was it the tallest timber building in the world at 51 meters.

3.3.4 Brock Commons

Brock Commons is a 54-meter-tall student housing located at the University of British Columbia's campus in Vancouver, Canada. This building is the first mass timber, structural steel, and reinforced hybrid structure that reaches 18 stories in Canada. The structural system of this building consists of two concrete cores that stabilize the building against vertical loads and CLT floor panels held up by timber columns. The CLT-panels act in a two-way action, which could be compared to a cast-in-situ flat slab, and are used together with the timber columns as a structural system on floors 2-18. The first floor is made out of concrete. Steel was used for the connections, the roof, and the prefabricated steel-stud framed laminated panel window wall system (Canadian Wood Council).

Two central problems with tall timber buildings are fire and acoustics requirements. For Brock Commons, the mass timber was encapsulated with gypsum boards to provide two-hour fire resistance, and concrete was used for the cores and first floor. Sprinkles were also installed on every floor, and a fire alarm system. A fire pump and a 20 000-liter backup water supply tank were installed below the ground floor slab, run by an independent emergency power source. A 50 mm concrete layer was placed on top of the CLT panels to enhance the acoustical properties of the floor (Canadian Wood Council).

One of the struggles when designing Brock Commons was code compliance. The construction of tall timber buildings on campus in the British Columbia building code had a 6-story restriction. Therefore, it was required to submit a proposal of the Brock Commons concept, which was heavily reviewed and questioned. The design team of Brock Commons developed design concepts and proposed strategies for mitigating the critical areas of technical risk. To comply with the code, a site-specific regulation for tall wood buildings was created (UBC Tall Wood Building Regulations). This regulation was reviewed by both local and international experts (UBC Sustainability, n.d.).

Figure 3.9 Brock Commons, taken spring 2022.

3.3.5 Origine

In 2017, a 13-story building called Origine was finished in Quebec, Canada. At the time, was this the world's tallest building with a structural system made entirely of wood. The structural system consists of CLT-shear walls designed to resist lateral loads or vertical loads. Additional glulam posts and beams were used to help with the loadbearing. Unfortunately, like Brock Commons, did Origine have trouble complying with the building code that did not have clear regulations for tall timber buildings and restricted the height of buildings. An alternative solution that would be equivalent measurements to the code was required to be shown to design Origine. Thanks to government support, the designers could conduct testing and research in a lab to develop solutions for building with wood and show that a 12-story wood building could meet the building code, which later was used as foundation for changing the Canadian building code (Cecobois, 2018).

Origine opted for a hybrid solution when it comes to fire resistance. Gypsum was added on top of the timber elements to postpone the parts from burning in case of a fire. The elements were also seized so that the charring together with the gypsum boards would last at least 2 hours in a fire which complies with the Canadian building code for tall timber buildings (Cecobois, 2018).

4 Questionnaire

Working professionals in Scandinavia and Canada were contacted to understand the challenges of designing tall timber buildings and how to comply with the building codes and practices when doing so. A questionnaire was made and either sent out to working professionals or used as a base for an interview. See Appendix A for the complete questionnaire and answers. With the responses from the questionnaire and the interviews were the following questions hoped to be answered:

- Is there an upgoing trend for tall timber buildings?
- What are the main obstacles when it comes to designing tall timber buildings?
- Are there any parts of the design code/building practice for designing tall timber buildings that are easier to understand?
- Are there any parts of the design code/building practice for designing tall timber buildings that are harder to understand?

The goal of the questionnaire is to get an idea of what experts in the fields think about the design process and legislation for tall timber buildings and to compare the answers coming from Scandinavia with the ones from Canada.

4.1 Summary of the Answers

Following is a summary of what the different experts in timber engineering answered on the questionnaire. Worth mentioning here is that the experts in Canada are located in the Vancouver area. The experts in Scandinavia are located in Sweden, with one exception where the expert is located in Norway.

4.1.1 Experts from Canada

The contacted experts in Canada have up to 30 years of experience working with timber professionally. They all had a similar perception of the use of timber in tall timber buildings. Most of them thought that less than 5 % of the tall buildings today have timber as the primary material in the structural system. Most of the experts agreed that this percentage would increase in the future, that in 20 years will 10-25 % of tall buildings use timber in the main structural system. However, a few thought it would still be less than 5 % or around 5-10 %. One of the experts mentioned the "Wood First Act" that makes the timber more prioritized in provincially funded buildings. This is in accordance with the Wood First Program in British Columbia, where the government encourages timber and innovation in the forestry industry. This approach is also similar in the province of Quebec (Government of British Columbia, 2009).

The experts in Canada mention several obstacles that they think are the main problem in designing tall timber buildings. Building codes and their limitations are brought up, especially regarding the fire rating. The financial part of building tall buildings in timber is also mentioned. That developers, insurance, and financial institutions' perception of tall timber buildings need to change to enable more tall timber buildings to come into the market.

Several experts mention that the fire rating system is complex to understand in the building code and limits the design. One expert says that structural approval is more accessible than fire approval. Several answers state that the lateral loads are hard to satisfy and that the seismic and wind loads are complex and need special attention when designing tall timber buildings.

According to the experts, is the early design phase for tall timber buildings extra important. A clear concept where fire and seismic design are considered early sets the tone for the rest of the project. It is also important to have clear communication and establish trust with everyone involved in the project. One expert says that suppliers need to be involved early, which some owners do not like because it makes them feel like they cannot get out of it once the suppliers are involved.

Some final thoughts from the experts in Canada are that this is an evolving field and will take time to adopt. Many are "inventing the wheel over and over again" which is normal, and sharing information and experience is essential to further the development of guidelines, codes, and the use of timber. One expert also thinks that transitioning the building codes in Canada to become more performance-based would help support the design and approval of tall timber buildings.

4.1.2 Experts from Scandinavia

The answers from the experts in Scandinavia show that they believe that timber will be used more frequently when designing tall buildings in the future. The answers indicate that timber is today used for around 5 % of the tall timber buildings being built, but they think that will increase to approximately 10-25 % in 20 years.

According to the experts asked in Scandinavia, are the main obstacles to designing tall timber buildings the dynamic behavior of tall timber buildings, fire regulations, and acoustic requirements. It can be rather hard to comply with the codes that consider these areas. ULS – requirements are much easier to understand and comply with. It is also commented that some parts of the codes are not written for a lightweight material like timber, and the code is lacking in some respects when it comes to timber products. According to one expert, the code regarding fire design is not very clear and can create time-consuming discussions. Experts also mention that moisture and the economic aspect of building with timber is an obstacle and needs to be considered. Lack of knowledge and technical knowledge among the contractors and designers can also be a problem.

The experts agree that extra focus needs to be put on dynamic behaviors and fire design when designing tall timber buildings. An expert also mentions how valuable and important it is for every part involved in the design to avoid errors later in the design phase. Another expert mentions the lack of inspection throughout the whole building process and that it should be improved.

Some final words from one of the experts point out the reasonability of having tall buildings using only timber as the main building material. It might be better to use timber where its potential and characteristics shine and other materials when suitable, creating more material-effective buildings.

4.2 Comparison and Discussion

The answers from experts from the different regions are similar, but there are some differences. The experts from both areas think that the use of timber in tall buildings will increase, but there are still many things that can be improved. Building codes and regulations that need to be updated for tall timber buildings were brought up by experts from both areas but more frequently by the experts in Canada. Many experts also mention that the dynamic response in timber buildings and the fire design are two obstacles that are very time-consuming and tricky to design. A difference here is that experts in Canada name the difficulty of designing for the seismic load, which the experts in Scandinavia do not have to consider. The question about money in different aspects is also mentioned by experts from both areas as an obstacle.

Interestingly, an expert in Canada mentioned that making the building code in Canada more performance-based would make the approval of tall timber buildings easier. An indication of how the building practice in Scandinavia might be more performance-based compared to Canada is how in Scandinavia there exist buildings like Mjøstårnet and Sara Kulturhus, both tall timber buildings made entirely out of timber and have open visible timber surfaces. In Canada are timber elements often encapsulated. An expert in Scandinavia also questions if using only timber in tall timber buildings is a good use of material and might be better to incorporate other materials.

5 Design Process for Tall Timber Buildings

Both Canada and Scandinavia have different building codes and practices that affect how tall timber buildings are designed. In this chapter, some of the main obstacles when designing tall timber buildings will be examined and compared to how these differ in Scandinavia and Canada. Again, Sweden will be used as a representative for the Scandinavian countries.

5.1 Fire

The fire design is even more critical when it comes to taller buildings compared to low-rise buildings. This is because a taller building takes longer to evacuate, and it is harder for firefighters to reach and save in a tall building. A safe fire design aims to have a sufficient structure for a set amount of time during a fire, keep the development of the spread of fire and smoke limited, and not spread the fire to the surrounding buildings. It is also vital that the people inside the building can be evacuated and saved safely.

5.1.1 Sweden

Building classes in Sweden are based on the needed fire protection (Boverket , 2011) and are rated from B0 to B3. The definitions are as follows:

- Br 0: Buildings with extremely high fire protection requirements. Buildings with more than 16 stories must be designed analytically.
- Br 1: Building with high fire protection requirements, primarily buildings with over two stories.
- Br 2: Buildings with moderate fire protection requirements, primary buildings with 1-2 stories.
- Br 3: Buildings with low fire protection requirements, primarily single-story buildings.

Tall timber buildings are automatically placed in either Br 0 or Br 1 and require high fire protection. In addition, the additional analytical design needed for Br 0 requires designers to have a more comprehensive design than the simplistic design used for the other building classes.

There is also a classification system for each building part, a combination of the letters REI and a number between 15 and 360 representing the time the element should last in a standardized fire (Boverket , 2011). The letters REI means the following:

- R: Load-bearing capacity
- E: Integrity (airtightness)
- I: Insulation

Eurocode (SS-EN1995-1-1:2004, 2004) describes how the charring depth can be calculated or how much gypsum needs to be added to a structural element to provide a sufficient load-bearing capacity (R). Calculating the insulation time and preventing the spread of smoke and fire (E and I) are also explained. Gypsum can also be a valuable tool to improve the fire capacity in these aspects.

The classification of the REI system can vary a lot from building to building. However, compared internationally are the fire requirements in Sweden relatively low. For example, if an automatic sprinkler system is installed or if there if a fire brigade can put out the fire within 60 minutes, it is the highest load-carrying time requirement of 90 minutes, independent of the fire load intensity (Jönsson & Lundin, 1988).

According to a report regarding fire safety in high-rise buildings in Sweden (Nystedt & Rantatalo) is the national board of housing in Sweden not updated enough to handle high-rise buildings with over 16 stories. Therefore, an analytical design is needed and is performed by analyzing the associated fire risk in tall buildings to ensure humans' safety and have a good evacuation strategy. Since the code change in 2002 are two staircases needed in a building taller than 16 stories to help with the evacuation in case of fire. There is still a lack of guidelines for the fire safety of tall buildings. Therefore, a proposal was made by Nystedt and Rantatalo that another approach could be made for high-rise buildings. Instead of rating the load-bearing elements as 90 minutes, there should be a requirement based on the time of complete evacuation and total burnout of a fire compartment or fire section. For this requirement, could the fuel load be calculated to estimate the evacuation time.

A paper by Brandforsk (Brandon & Östman, 2018) gives proposals on how to get a multi-story timber building fireproofed. The focus here is to prevent the fire from spreading, which can happen in three ways: Direct fire through fire cells, fire and smoke spreading through cavities and spreading from the outside (for example, along the façade or through the window). To prevent the spread bring this article up the importance of boards, where gypsum is the most common, and how they can be placed to avoid the spread of fire. The importance of placing the gypsum board correctly in relation to the structural members and the correct way to mount installation is also mentioned. Again, this is to prevent the spread of fire, see Figure 5.1 and Figure 5.2 for an example of a correct and incorrect way to do it.

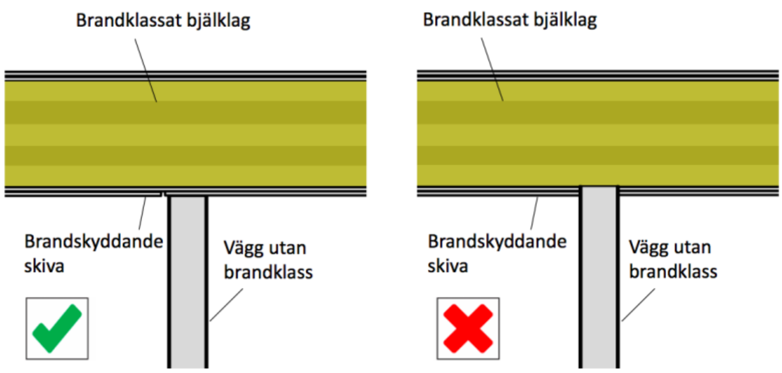


Figure 5.1 Correct relation between gypsum and joist to have ongoing fire protection (Brandforsk.se). Republished with permission.

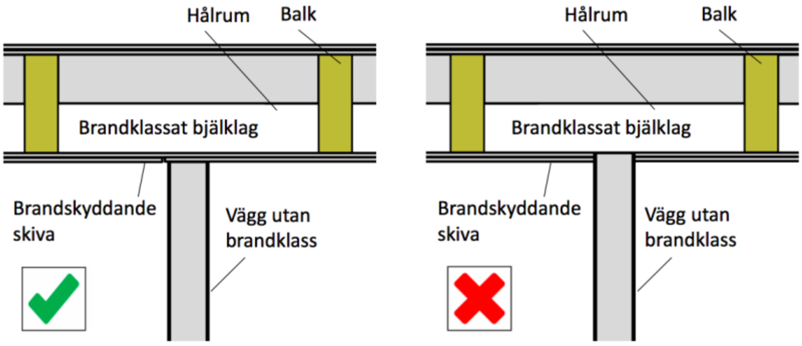


Figure 5.2 Correct mounting of a correct fire-rated lamp. (Brandforsk.se). Republished with permission.

5.1.2 Canada

In the National Building Code of Canada (NBCC) (2015), there are four main objectives for fire design. These are in broad and qualitative terms and are that the design must provide: safety (OS), Health (OH), Accessibility for the disabled (OA), and fire and structural protection of buildings (OP). As these are broad terms, are there also sub-objectives linked to a design regarding fire resistance. These can be functional statements that are more detailed and objective. Some examples of these are as follows:

- F01 – To minimize the risk of accidental ignition
- F02 – To limit the severity and effects of fire or explosions
- F03 – To retard the effects of fire on areas beyond its point of origin
- F04 – To retard failure or collapse due to the effects of fire

For fire design, building materials are categorized into combustible and noncombustible. Today, timber buildings are categorized as combustible buildings. Even though, when designed correctly can provide the same level of life safety and property protection as a noncombustible building (Canadian Wood Council , 2022).

The national building code of Canada (2015) lacks current regulations for fire design for timber buildings, especially when they are tall. Timber being considered a combustible material also makes it harder to comply with the existing fire regulations because it needs to provide an alternative solution that demonstrates equivalent performance. FPInnovations, a private nonprofit company specializing in everything regarding timber, have created a guide (Karacabeyli & Lum, 2014) for designing and constructing tall wood buildings in Canada. This guide exists to help create alternative solutions that can be used to create a safe fire design at the same level or better than what is required in the building code. The different alternatives presented in the technical guide from FPInnovations show other solutions on how the structural members can be encapsulated to be sufficient to comply with the two-hour resistance fire rating prescribed for a tall building of noncombustible construction according to the national building code of Canada (2015). The encapsulations can be divided into complete capsulation, limited encapsulation, and suspended membrane-type encapsulation, see Figure 5.3. A description of the different encapsulations is as follows (Karacabeyli & Lum, 2014):

- A complete capsulation would mean covering all the structural timber elements with a material (commonly gypsum) that could last the fire requirement of 2 hours. This would be a conservative approach, given that timber already has a level of protection on its own.
- Limited capsulation would mean that a limited amount of material is used to encapsulate the structural member. Fire has two stages, pre-flash over and post-flashover. Pre-flashover is the ignition and the growth of the fire and is the most important phase where the timber needs to be encapsulated. During post-flashover, is ventilation the governing factor of the spread of fire. Limited encapsulation uses this to lower the amount of material used to encapsulate and prove that it is enough to provide equivalent performance compared to what is required in the national building code of Canada.
- Suspended membrane-type encapsulation is when a membrane ceiling is suspended below a ceiling cavity. What is essential here is to ensure that the assembly provides enough fire-resisting rating and that a fire in the cavity does not spread excessively. This method would require incorporating the sprinkler system in the design to protect the void spaces where exposed combustibles would be located to prove that this design is adequate.

A fully-exposed solution could be possible, meaning that the charring of the timber is calculated. Then, the elements are dimensioned accordingly to last the fire requirement of 2 hours. However, this alternative is not yet fully developed and would need more resources and time to prove that it can provide the required level of performance.

In the national building code of Canada (2015), all buildings taller than six stories must be installed with a sprinkler system, which is a very effective way of controlling fires. The use of sprinklers can be used together with one of the encapsulation methods to prove a good fire resistance design as long as the reliability of the sprinkler system is good enough. This could mean that an onsite secondary water supply needs to be installed or a provision of redundant fire pumps with power sources (Karacabeyli & Lum, 2014).

The national building code (2015) contains several performance-based solutions for tall buildings. The main concerns are the limitation and added complexity that firefighters experience with taller buildings and the stack effect and its effect on the smoke movement in tall shafts. The action that can be done to aid the firefighting is mainly to limit smoke movements, have a voice and alarm system, and make the emergency operation as simple as possible using the design of the elevators.

The stack effect is created when the temperature inside the building is a lot different from the outside temperature. The difference causes pressure that grows depending on the height of the building. Smoke can mitigate through timber joists and protect shafts and staircases should the shafts be encapsulated to prevent the stack effect (Karacabeyli & Lum, 2014).

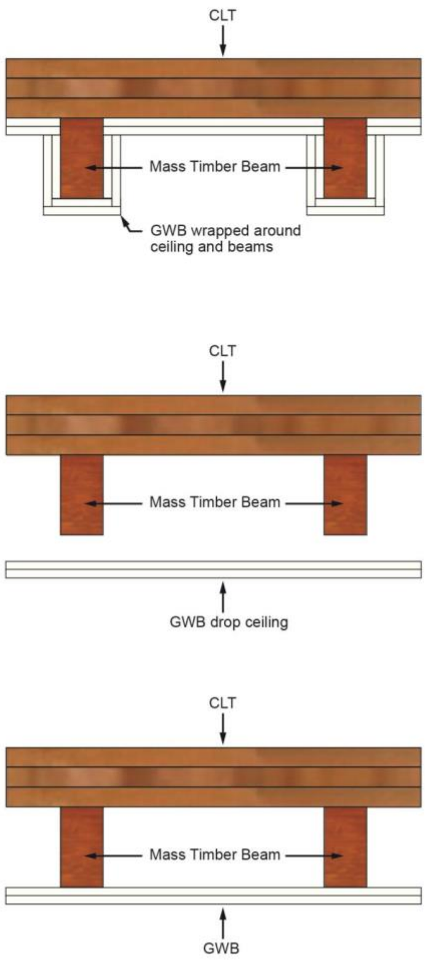


Figure 5.3 Examples of suitable approaches to encapsulating timber elements (FPInnovations). Republished with permission.

5.1.3 Comparison

The fire design for timber buildings is essential and requires much thought. In Scandinavia and Canada are the guidelines pretty similar when it comes to fire requirements. For example, they both have a time requirement for the bearing capacity of structural members and how that requirement can be met by either encapsulating the timber or calculating a charring depth so that the element can be sized accordingly. Both codes also address the importance of keeping the spread of fire and smoke low and having operational exit plans. The codes are also similar in the lack of it regarding the fire design of tall timber buildings.

The main difference between the Canadian and the Swedish building code and building guidelines is the level of safety requirements. For example, Sweden has a lower time requirement of 1.5 hours for structural elements in a tall building than Canada's 2 hours. Canada's building code and practice also require a higher encapsulation level than a Swedish design, mainly because timber is considered a combustible material and thus making the fire design more demanding. An example of how the fire design can be more liberal in Sweden is the difference between Sara Kulturhus and Brock Commons. Sara Kulturhus has open timber elements that are only treated with a flame-retardant varnish and a sprinkler system with an added battery-driven pump as an added security.

Brock Commons, where the timber is encapsulated in gypsum, has a sprinkler system with an on-site backup water tank and fire pump.

Green (2012) created an interesting cost comparison where the charring and the encapsulation method get compared. This is done by looking at a design for both a 12- and a 20-story building in various regions of Canada built with a FFTT-structural system where both the charring and encapsulation method is used. In addition, a 12- and 20- story concrete frame building is also used to understand what a more conventional building usually costs. Based on this comparison, the charring method for a 12-story building is around 5-6 CAD/square feet cheaper than the encapsulation method and 0-9 CAD/square meter cheaper than the 12-story concrete frame. For the 20-story building, the charring method is 6-7 CAD/square feet cheaper than the encapsulation method and is either 2 CAD/square feet more expensive or 3-7 CAD/square feet cheaper, depending on where in Canada it is built.

The limitation in the Canadian fire design makes it more costly, harder to comply with, and makes the building less flexible than the Swedish design, where the architect's vision of fully exposed timber elements can be more easily met. The building code's main problem is the classification of timber as a combustible material, even though it may have a similar fire safety to non-combustible materials or even better. The building code needs to be more precise when it comes to fire design in tall timber buildings and apply research regarding the fire safety of timber to make it more accessible.

5.2 Acoustics

Keeping the sound at a reasonable level becomes more challenging for timber buildings. Some of the reasons timber is worse than concrete are its need to have joints to a higher degree, which can cause flanking noise and lightness that causes low frequencies to transfer through more easily (Preager, 2019). Keeping a good sound quality in buildings is vital for humans' comfort and health.

5.2.1 Sweden

According to the Swedish national board of housing (Boverket , 2011), a building should be designed to limit disturbing noise and keep a sound level that is not harmful. Examples that need to be damped are noise from outside the building, adjacent apartments, installations, and elevators. Reverberation time also needs to be considered, which is the time it takes the sound to drop 60 dB from the start of the sound. This is especially important in hallways, where no furniture can act as dampers. According to Swedish standards (SS25268:2007, 2007), is the requirement for reverberation time 1.5 seconds for staircases and 1.0 for hallways.

In the Swedish standards (SS25268:2007, 2007) (SS25267:2015, 2015) are there different sound classifications which range from A to D. Sound class A has the most demanding requirements, sound class C is the minimum requirement, and sound class D has the least amount of requirements and is preferably not used. The sound requirements vary depending on what kind of building it is and what part of the building it is. For example, the requirements for a bedroom are more demanding than the rest of the apartment. The differences between the sound classes are 4 dB meaning that sound class A is 4 dB better than sound class B, and sound class B is 4 dB better than sound class C, and so on.

Sound can travel in different ways and from different sources. Following are some of the most important requirements needed to fulfill the minimum requirements, sound class (Boverket , 2011).

- Impact sound requirement is noise coming from induced forces that cause vibrations that are transferred through the portioning structural elements into other spaces, causing the noise. A typical example of this is footsteps on a floor. The impact sound level requirement from spaces outside dwellings to spaces inside dwellings is a difference of 56 dB.
- The airborne sound requirement is what is required between two spaces. A sound level difference of 52 dB is required from outside the dwelling space to the inside.
- Noise from installations and elevators is not required to have a higher equivalent sound level than 25 dB and not a higher maximum sound level than 35 dB for daily social activities and sleep areas.
- Noise from outside should not have an equivalent sound level higher than 30 dB and not a higher maximum sound level than 45 dB.

Flanking sound transmissions are an issue when it comes to tall timber buildings. According to Klas Hagberg (2019), this issue is even more significant for taller timber buildings where the statics and stability demand tight connections between the structural elements. Therefore, separating the elements by intermediate elastomers between floors/apartments is no longer applicable. Options to solve this are to accept a little more transmission via particular walls and reduce the quantity of elastic membrane or leave it out entirely if other walls are clad on one side. Alternatively, nodes can be built in by adding layers to the wall asymmetrically. Having asymmetric layers on each side is good as it helps to avoid interacting resonance and ensures the wall's sound insulation performance. The perks of adding these asymmetrical layers are that sound insulation class B can be achieved vertically and horizontally, but the disadvantage is that there is no exposed wood.

Some rules of thumb can be used for the acoustic design of tall timber buildings (Brandt, 2014). The sound class requirement should be put to C, but work should be done to get as close to class B as possible, focusing on owe frequencies and impact sound insulation. Other recommendations are that the floor structure should be at least 500 mm thick, site inspections should be conducted before painting, and some extra focus on where and how installations are installed.

5.2.2 Canada

In the national building code of Canada (2015), there are two ways airborne soundproofing can be classified, either by using the sound transmission class (STC) or the apparent sound transmission class (ASTC). STC has been more widely used in the past, where the requirements have been to have a separating assembly that provides a STC of no less than 50. For construction, separating a dwelling unit from an elevator shaft or a refuse chute is the STC rating no less than 55. If the ASTC rating would be used for a separating assembly and adjoining construction, is a rating of 47 sufficient. There is also an impact insulation class (ICC) which is set to 50 to be able to handle impact sounds.

ASTC includes flanking sound transmission path and direct sounds, whereas the STC rating ignores the contribution from flanking. The ASTC rating is becoming the new norm because of this difference, especially in timber buildings where disturbance due to flanking transmissions is prominent. More detailing regulations concerning flanking sound transmission paths were added to the national building code in 2015.

The international code council (ICC) (2010) has also created a guideline for acoustics to contribute to public health, safety, and the general welfare of the built environment. This guide provides two grades of acoustical performances regarding acceptable and preferred acoustic performance and a guide on how to consider flanking transmission sounds. The acoustical grading is divided into grade A, which represents preferred performance, and grade B is acceptable. See Table 5.1 and Table 5.2 for how grading A and B is done depending on if the measurements are done in the field or the laboratory.

Table 5.1 Grades of Field Acoustical Performances

Field Sound Rating	Acceptable performance (Grade B Performance)	Preferred Performance (Grade A Performance)
Airborne Noise	52	57
Impact Noise	52	57

Table 5.2 Grades of Laboratory Acoustical Performance

Laboratory Sound Rating	Acceptable performance (Grade B Performance)	Preferred Performance (Grade A Performance)
Airborne Sound	55	60
Impact Sound	55	60

5.2.3 Comparison

The requirements for the acoustic design are similar between Canada and Sweden. Both have similar requirements for airborne and impact sounds and how the sound performance can be graded where Sweden has a grade from A to D and Canada grades A and B. The acceptable performance in Canada (grade B) is similar to Sweden (Grade C), and the preferred grade in Canada (Grade A) corresponds to Swedish grade B. A difference here is that Sweden has additional gradings that they can use. However, tall timber buildings where it is hard to optimize the acoustics performance are the acceptable and preferred performances enough.

The differences found in the Canadian and Swedish codes are minor. There are mainly some different details, and the sound requirements change depending on the building and location instead. However, what is important is to include the acoustic design early in the project. As shown in Figure 5.4, taken from the Swedish CLT handbook (Gustavsson, et al., 2019), the cost of noise counter measurement increases significantly after the planning phase is done.

It seems like the code in both Canada and Scandinavia is clear, and the issue is instead to comply with them in timber buildings where sounds are transmitted more easily. Therefore, is a timber-concrete composite floor chosen in many tall timber buildings because concrete provides better sound insulation (Schmid, 2005). There is also a guide created by the Canadian company FPInnovation on designing timber-concrete composites two enhance the two materials' structural properties and increase the sound insulation compared to using only timber as a material (FPInnovations, 2020).

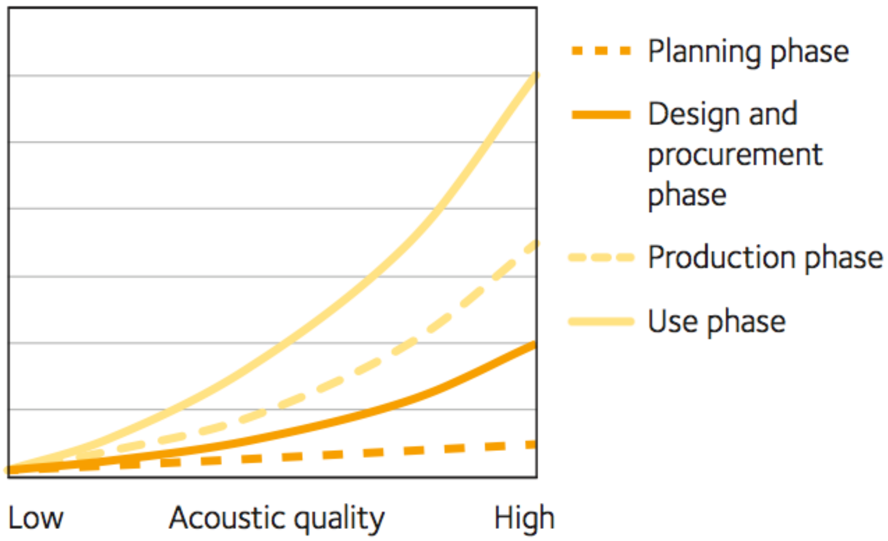


Figure 5.4 Costs of noise countermeasures in different building phases (The CLT Handbook). Republished with permission.

5.3 Vibrations

Vibrations are a vital comfort criterion, especially for taller buildings. It is caused by dynamic forces, which can come from sources like people walking around in the building or from dynamic wind loads. According to the Swedish CLT handbook, vibrations from people can be divided into two categories: Floor sagging describes the experience of a self-generated vibration, and oscillation describes how a person perceives floor vibrations caused by other people.

When it comes to vibrations, it is essential to look at the natural frequency and acceleration of the building. A paper by Edskär (2018) describes how a structural system made of steel and concrete has a frequency commonly around 1 Hz. In contrast, timber and timber-hybrid buildings usually reach a frequency between 1-4 Hz. Edskär also describes how the natural frequency of a building can be reduced by adding mass, which is suitable to do to buildings with a frequency below 1 Hz. In addition, increased stiffness increases the natural frequency and reduces the acceleration level, suitable for buildings with a natural frequency over 2 Hz.

5.4 Sweden

Guidelines for these criteria are based on the user's perception of motion, where high acceleration levels can even cause nausea. Different international standards handle horizontal vibrations in buildings and the human perception of vibrations. There are ISO 6897, which covers the ranges from 0.063 Hz to 1 Hz, and ISO 2631-2, which covers the range of 1-80 Hz. These two use the Root Mean Square (RMS) value for the acceleration due to a maximum wind velocity with a return period of five years. ISO 10137 covers the range from 0.063 Hz to 5 Hz and uses peak acceleration calculated for a wind velocity with a return period of one year (Johansson, Linderholt, Jarnerö, & Landel, 2016). See Figure 5.5, which shows the limitations on the frequency and acceleration of vibrations caused by the wind for residential and office buildings.

ISO 2631-3 also states limitations in acceleration to ensure human comfort. The acceleration limit ranges from around 0.005 to 0.063 m/s2, depending on the natural frequency of the floor.

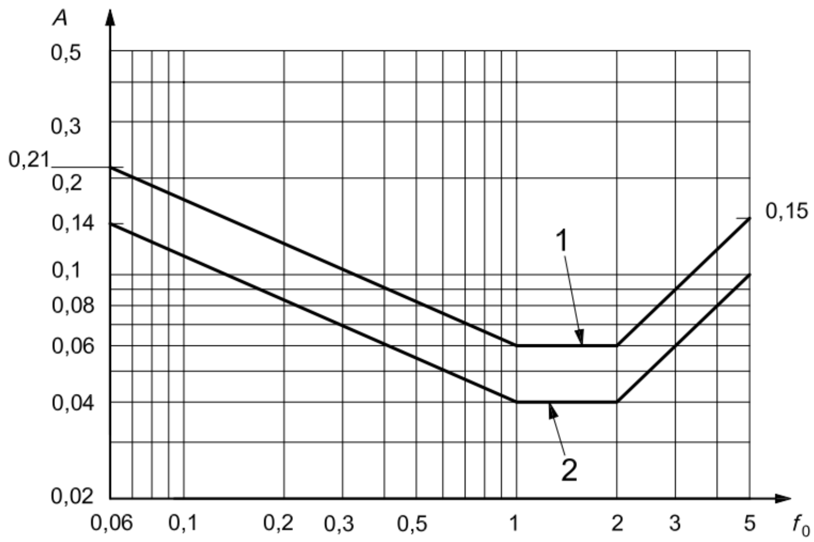


Figure 5.5 Acceleration vs. natural frequency from wind-induced vibrations with the limit 1 for offices, and a limit 2 for residencies (SS-ISO 10137-2008). Republished with permission.

5.5 Canada

According to NBCC should an analysis regarding wind vibration serviceability of a building be checked if the building meets one of the following criteria:

- The building height is greater than four times its minimum effective width.
- The building height is greater than 120 m.
- The building is lightweight.
- The building has low frequencies.
- The building has low damping properties.

The vibration limit should lay around 1-3 % of the acceleration due to gravity (g). The limit of 1.5 % of g was generally used for residential buildings, and the limit of 2.5 % of g was generally used for offices. However, according to Dagenais (2016), is it questionable to use these limits for tall timber buildings. It would be good to measure the wood building acceleration after completion, get feedback from the occupants if they have any discomfort from vibration, calculate the peak acceleration, and compare it with the test results and the feedback from the occupants of the building.

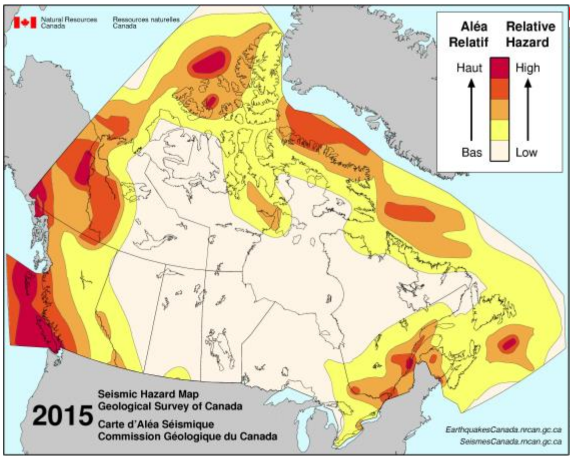
The national building code of Canada (2015) also has recommendations on floor acceleration limits. Here it can be seen that for office and residential is the limit 0.4 to 0.7 % of g for regular use and 4 to 7 % of g if the intended area purpose is rhythmic activity.

5.6 Comparison

Both Scandinavia and Canada have a similar approach to the acceleration limit, both for the building itself and floor elements. The limitations are different between the two places, but marginally. Instead, the question is if these limits are a good application for buildings and elements made out of timber. The performance of different timber structures is also unclear, so it is essential to be careful and perform different safety measurements as suggested by FPInnovations, such as vibration measurements after building completion, talking to the occupants, and comparing with numerical calculations.

5.7 Seismic Design

The seismic load is the most significant difference when designing buildings in Canada and Scandinavia. The seismic activity in Canada and British Columbia can be seen in Figure 5.6. As seen on these maps are there areas in Canada where seismic activity is high, especially on the west coast. The seismic load caused by earthquakes is a huge design factor that must be designed accordingly.



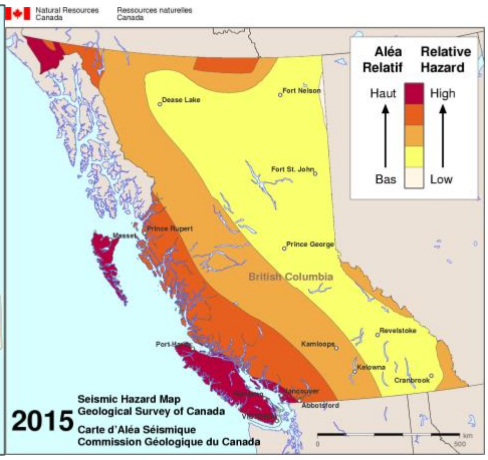


Figure 5.6 Maps show the seismic activity in different areas of Canada. (Government of Canada, 2021). Republished with permission.

Different wood-based systems are mentioned in Canada's national building code that can achieve a good seismic force-resisting system (SFRS). These are wood-frame shear walls, braced frames, and moment-resisting frames (Karacabeyli & Lum, 2014). These systems have a different force modification factor representing how well they can handle seismic load based on testing and are used for earthquake design. According to the national building code of Canada (2015), the intent of the seismic design is for a building to be able to ensure the following:

- Ensure a safe design that protects the life and safety of the building's occupants and the general public in the event of strong ground shaking.
- During low and moderate levels of ground shaking, the damage done to the buildings is limited.
- Post-disaster, the building can continue to be occupied and functional even after a strong ground shaking.

There are different procedures for analyzing how well a building handles seismic force. For example, equivalent static procedures can treat the dynamics forces from an earthquake as static ones that are equivalent. However, this does not account for the dynamic characteristics created by an earthquake. Still, it is sufficient and suitable for tall timber buildings less than 60-meter-tall and does not have periods higher than 2 seconds. Otherwise, a dynamic approach should be used, with two to choose from, Response spectrum analysis (also called modal analysis) and time history linear dynamic analysis.

The response spectrum analysis has become a default in Canada's national building code because of today's computers. The analysis is a method where the structural response to short transient dynamic events is estimated. It is based on a particular type of superposition. The idea is to provide an input that limits how much an eigenmode having a specific natural frequency and damping can be excited by an event of this type (Comsol , 2022). Linear response history analysis is a numerical method used to determine the response of a mathematical structural model to either an actual recorded earthquake or an artificial earthquake (Aswegan & Charney, 2014). The linear response history analysis can also be performed nonlinearly.

To perform these analyses are several parameters needed. The following are the more important ones (Karacabeyli & Lum, 2014):

- Element properties
- Effective damping
- Input earthquake motions for analyses
- Models for connections and assemblies
- Soil properties and soil-structure interaction

The damping of a building differs depending on what material and which structural system is used. FPInnovation studied the damping of low- and mid-rise wood buildings with different structural systems like light wood frame, post and beam, CLT, and combinations of various systems (Karacabeyli & Lum, 2014). They concluded that the equivalent damping coefficient is 2-4% and that 3% would be a reasonable assumption for critical damping. Another study on the damping effect of wood buildings from Edskär (2018) also found a variation in the damping effect and had the conclusion that proper damping would be 1.9 % for post and beam systems, 2-2.5 % for CLT structures, and 2-3 for hybrid structures.

The seismic design can also be improved by introducing energy dissipation devices such as viscous dampers and base isolation. Base isolation means that a layer between the ground and the building is put in so that layers deform instead of the building in case of an earthquake. The low horizontal stiffness of the layer creates a much longer fundamental period than a building on a fixed base. Installing energy dissipation devices (dampers) would also help with the seismic design by absorbing or dissipating energy and thereby reducing the seismic response of the building (Karacabeyli & Lum, 2014). See Figure 5.7 for how an energy dissipation device can be installed on an elevator shaft made of CLT.

Figure 5.7 Example of an energy dissipation device.

6 Loads

The following chapter explains the calculations process performed for the computer modeling. It focuses on how wind and seismic loads are calculated. Equations are taken from the national building code of Canada (2015). The process is similar in Scandinavia but with some different factors used. The main difference is the calculations for seismic loads.

6.1 Wind Load

There are three different approaches in the Canadian national building code (2015) regarding wind load. Generally is a static approach used, but for dynamically sensible buildings is either a dynamic- or wind tunnel procedure used. A building is dynamically sensible if one or more of the following criteria are fulfilled.

1. Its lowest natural frequency is less than 1 Hz and greater than 0.25 Hz.
2. Its height is greater than 60 m.
3. Its height is greater than 4 times its minimum effective width, where the effective width, *w*, of a building shall be taken as, where the summations are over the height of the building for a given wind direction, is the height above grade to level *i*, and is the width normal to the wind direction at height: the minimum effective width is the lowest value of the effective width considering all wind directions.

For the static procedure is Equation 6.1 used to determine the wind load.

$$p = I_w q C_e C_t C_g C_p \tag{6.1}$$

Where:

$p =$ Specific external pressure acting statistically and, in a direction, normal to the surface, considered positive when the pressure acts towards the surface and negative when it acts away from the surface.

$I_w =$ Importance factor for wind load.

$q =$ reference velocity pressure.

$C_e =$ Exposure factor.

$C_t =$ Topographic factor.

$C_g =$ Gust effect factor.

$C_p =$ External pressure coefficient.

The dynamic and wind tunnel procedure is slightly different from the static procedure. The dynamic procedure should follow the same steps as the static procedure, except that the exposure factor, C_e, and the gust effect factor, C_g, will be determined differently. The wind tunnel procedure considers surrounding buildings and their sheltering effect and tests on scale models to determine wind loads. To determine if a dynamic procedure is needed or not, can the lowest natural frequency be calculated using Rayleigh's method that is based on the deformation under static load, see Equation 6.2.

$$f_n = \frac{1}{2\pi}\sqrt{\frac{\sum_{i=1}^{N} F_i X_i}{\sum_{i=1}^{N} W_i X_i^2}} \tag{6.2}$$

Where

n = Number of stories.

F_i = Associated wind force of each story.

X_i = Horizontal deflection of each story caused by F_i.

W_i= Associated mass of each story.

6.1.1 Dynamic Procedure

The dynamic procedure uses Equation 6.1 similarly to the static procedure, but with changed values for the exposure factor, C_e, and the external gust effect factor, C_g. These factors can now be calculated using Equation 6.3 and Equation 6.4.

$$C_e = 0.5\left(\frac{h}{12.7}\right)^{0.5} \quad for\ 0.5 \le C_e \le 2.5 \tag{6.3}$$

The gust effect factor I calculated using equation 6.4.

$$C_g = 1 + g_p(\sigma/\mu) \tag{6.4}$$

Where

g_p = Statistical peak factor for the loading effect.

μ = Mean loading effect.

σ = Root-mean-square loading effect.

Coefficient of variation, σ/μ, can be calculated using Equation 6.5.

$$\sigma/\mu = \sqrt{\frac{K}{C_{eH}}\left(B + \frac{sF}{\beta}\right)} \tag{6.5}$$

Where

K = Surface roughness coefficient of the terrain.

C_{eH} = Exposure factor at the top of the building.

B = Background turbulence factor.

s = Size reduction factor.

F = Gust energy ratio at the natural frequency of the structure.

β = Damping ratio in the along-wind direction.

Turbulence factor, B, is calculated using Equation 6.6.

$$B = \frac{4}{3}\int_{0}^{914/H}\left(\frac{1}{1+\frac{xh}{457}}\right)\left(\frac{1}{1+\frac{xw}{122}}\right)\left[\frac{x}{(1+x^2)^{4/3}}\right]dx \tag{6.6}$$

The size reduction factor, s, is calculated using Equation 6.7.

$$s = \frac{\pi}{3}\left(\frac{1}{1+\frac{8f_nH}{3V_H}}\right)\left(\frac{1}{1+\frac{10f_nw}{3V_H}}\right) \tag{6.7}$$

Where

$H =$ Height of the building.

$w =$ Effective width of the windward face calculated as $w = \frac{\sum h_i w_i}{h_i}$, where w_i is the width normal to the wind direction at height h_i.

$f_n =$ Lowest natural frequency of the building, in Hz.

$V_H =$ Is mean wind speed and is calculated $V_H = 39.2\sqrt{I_w q C_{eH}}$.

The gust energy ratio at the natural frequency, F , of the structure is calculated with the help of Equation 6.8 and Equation 6.9.

$$F = \frac{x_0^2}{(1+x_0^2)^{4/3}} \tag{6.8}$$

$$x_0 = 1220 f_n / V_H \tag{6.9}$$

The statistical peak factor, g_p, is a function of average fluctuation rate and is calculated using Equation 6.10.

$$g_p = \sqrt{1\ln\,(3600\nu)} + \frac{0.577}{\sqrt{2\ln\,(3600\nu)}} \tag{6.10}$$

Where

$\nu =$ Average fluctuation rate calculated $\nu = f_n\sqrt{\frac{sF}{sF+\beta B}}$

6.1.2 Wind Induced Vibrations

Vibrations that are caused by the dynamic behavior of wind are also something that needs to be considered. A performance-based design approach would be to calculate the building's peak acceleration in the building caused by wind and compare them to limits where the occupants in the building start noticing them. Equation 6.11 and Equation 6.12 can be used to calculate the peak acceleration of a building in an across-wind direction, a_W, and in an along-wind direction, a_D. These should not be higher than 1.5 % of the acceleration due to gravity (g) for residential buildings and 2.5 % of g for office buildings.

$$a_w = f_{nW}^2 g_p \sqrt{wd} \left(\frac{a_r}{\rho_B g \sqrt{\beta_W}} \right) \tag{6.11}$$

$$a_D = 4\pi^2 f_{nD}^2 g_p \sqrt{\frac{K_s F}{C_{eH} \beta_D} \frac{\Delta}{C_g}} \tag{6.12}$$

Where

$w, d =$ across-wind direction effective width, and along-wind direction effective depth.

$a_r = 78.5 \cdot 10^{-3} \left[V_H / f_{nW} \sqrt{wd} \right]^{3.3}$

$\rho_B =$ Average density of the building.

β_w and β_D are fraction of critical damping in across- and along-wind direction.

f_{nW} and f_{nD} are fundamental natural frequencies in across- and along-wind directions.

Δ= Is maximum wind-induced lateral deflection at the top of the building.

$g =$ Acceleration due to gravity.

$g_p =$ Statistical peak factor for the loading effects.

$K =$ A factor related to the surface roughness coefficient of the terrain.

$s =$ Size reduction factor.

$F =$ Gust energy ratio at the natural frequency of the structure.

$C_{eH} =$ Exposure factor at the top of the building.

$C_g =$ Gust effect factor.

6.2 Earthquake Load

In general, both seismic and wind loads are dynamic. However, under certain circumstances, can they be assumed to behave as equivalent static loads. Same as the wind load can the seismic load behave dynamically. According to the Canadian national building code (2015) should the seismic load be designed according to a dynamic analysis procedure except when the following criteria are met, then the Equivalent static force procedure can be followed:

- If $I_E F_a S_a(0.2)$ is less than 0.35
- Regular structures are less than 60 m in height and have a fundamental lateral period, T_a , less than 2 s in each of two orthogonal directions.
- Structures with structural irregularity of type 1-6 or 8 that are less than 20 m in height and have a fundamental lateral period, T_a , less than 0.5.s in each of the two orthogonal directions.

The fundamental natural period for braced frames can be calculated using Equation 6.13 for shear walls and other structures can Equation 6.14 be used.

$$T_a = 0.025 h_n \tag{6.13}$$

$$T_a = 0.05 (h_n)^{3/4} \tag{6.14}$$

In the equivalent static force procedure can the minimum lateral earthquake force be calculated using the general equation 6.15.

$$V = S(T_a) M_V I_E W / (R_d R_o) \qquad (6.15)$$

Where:

$S_a(T_a) =$ 5% damped spectral response acceleration for the fundamental lateral period of vibration of the building.

$M_V =$ Factor to account for higher mode effect on base shear.

$I_E =$ Earthquake importance factor.

$W =$ Dead load.

$R_d =$ Ductility-related force modification factor.

$R_o =$ Overstrength-related force modification factor.

For moment-resisting frames, braced frames, and other systems, should the static force calculated from Equation 6.15 not be less than equation 6.16. And for a building located on a site other than Class F (where site-specific evaluation is required) and having a seismic force-resisting-system with an R_d equal to or greater than 1.5, should the static force shall not be greater than the larger of the value calculated using Equation 6.17 and Equation 6.18.

$$S(2.0) M_V I_E W / (R_d R_o) \qquad (6.16)$$

$$\frac{2}{3} S(0.2) I_E W / (R_d R_o) \qquad (6.17)$$

$$S(0.5) I_E W / (R_d R_o) \qquad (6.18)$$

If the period of the building exceeds 0.7 s will the total lateral seismic force V be distributed over the height of the building, according to equation 6.19.

$$F_x = \frac{(V - F_t) W_x h_x}{(\sum_{i=1}^{n} W_i h_i)} \qquad (6.19)$$

Where

$F_T =$ Portion of the load at the top of the building is calculated $F_T = 0.07 T_a V$, but does not exceed $0.25V$.

The structure also needs to be designed to resist overturning effects caused by the seismic loads. The overturning moment can be calculated using Equation 6.20.

$$M_x = J_x \sum_{i=1}^{n} F_i (h_i - h_x) \qquad (6.20)$$

Where

$J_x = 1.0$ for $h_x \geq 0.6 h_n$, and $J_x = 1 + (1 - J)\left(\frac{h_x}{0.6 h_n}\right)$ for $h_x < h_n$

7 Computer Modeling

A simplified model of Mjøstårnet and Brock Commons was created in the program *ANSYS* and studied to understand how the design might differ between these places. The computer modeling will focus on understanding how the buildings perform under lateral loads where a seismic load is the primary design difference that needs to be accounted for. The analyses that will be performed are as follows:

- Frequency analysis
- Lateral load analysis
- Vibration analysis
- Response spectrum analysis

These analyses will give a quick understanding of how the reference projects act under lateral loads and how the two reference buildings differ. Calculations made for analyses can be found in Appendix B.

7.1 Setting up the Models

The model based on Mjøstårnet was simplified to a 17-story building without the beams and columns on the roof. The area of the model is 15 x 35 meters with a height of 68 meters (each floor is 4 m), which is the height of the highest floor. Dimensions of the structural members are taken from (Abrahamsen R. , 2017) and are as follows:

- Glulam beams supporting timber floors: 395 x 585 mm^2 or 395 x 675 mm^2
- Glulam beams supporting concrete floors: 625 x 585 mm^2 and 625 x 720 mm^2
- Largest diagonal cross-section: 625 x 990 mm^2
- Internal columns: 725 x 810 mm^2 and 625 x 630 mm^2
- Corner columns: 1485 x 810 mm^2
- Concrete floors: 300 mm

Similar dimensions on beams, columns, and pillars are used. Concrete floors were used on the upper levels of the model, whereas timber floors were used on the lower floors. The floors used in Mjøstårnet are simplified into one element with a thickness of 0.4 meters.

The model based on Brock Commons is 53 m high with a 15 x 56 meters footprint. Each floor is 2.8 meters high except for the ground floor, which is 5 meters tall. The ground floor also has concrete columns and a concrete floor. The model also has two concrete cores and a post and platform system, just like Brock Commons. All the timber floors in Brock Commons also have a 50 mm concrete layer on top of them, and this will not be modeled. The dimensions of the structural elements are as follows:

- Concrete columns: 600 x 600 mm^2
- Concrete core: 6000 mm width, 5000 mm length, 450 mm thick
- Timber columns: 400 x 400 mm^2

- Concrete floor: 1000 mm
- Timber floor: 300 mm

Each element in the structures is connected with rigid connections. Floors in Brock Commons are connected to the elevator shaft. The pillars at the bottom of each model are clamped to the ground. The structural systems of Mjøstårnet and Brock Commons can be seen in Figure 7.1, and the models created in *ANSYS* can be seen in Figure 7.2.

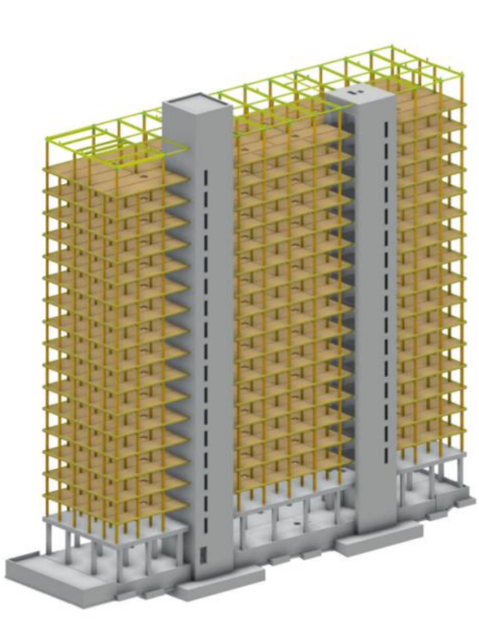


Figure 7.1 Figures show the structural models of Mjøstårnet (left)(Moelven.se) and Brock Commons (right)(Cadmakers). Republished with permission.

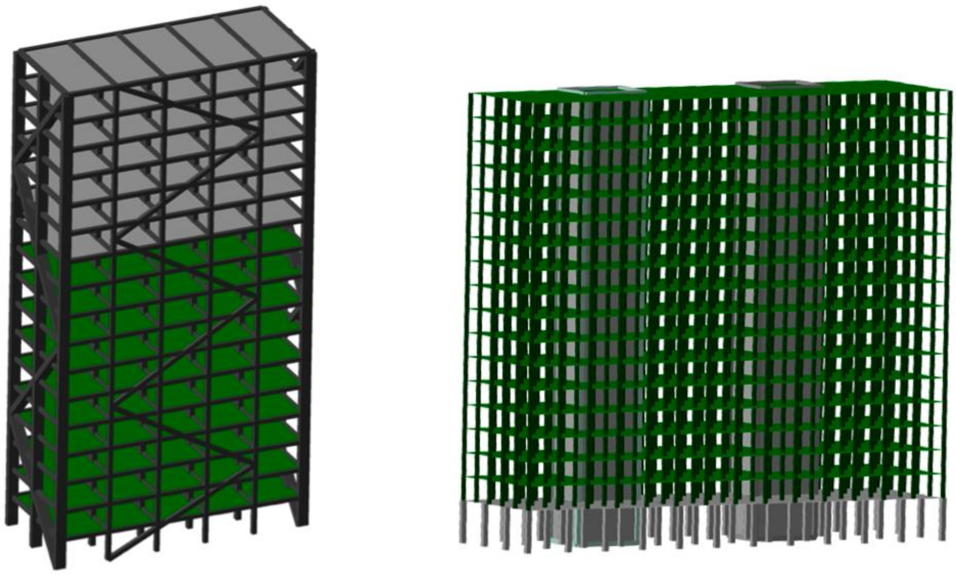


Figure 7.2 Models in ANSYS based on Mjøstårnet (left) and Brock Commons (right)

7.1.1 Loads

A gravity load will be implemented on all the elements in the models. A distributed load will be put on the timber floors in Brock Commons to add the extra weight that the 50 mm concrete layer that was not modeled would have given. In Figure 7.3 can the deflection based on the gravity load be seen. The largest compressive deformation occurs near the bottom of the model, but as the movement acts cumulatively is the largest movement at the top of the building. The models act as suspected, where the biggest deflection is shown in the middle for the Mjøstårnet and between the concrete cores for Brock Commons.

It was impossible to add an area load representing the wind load because façade elements were not computed. Therefore, was the wind load distributed with the help of point loads on nodes where the floors and columns are connected to the facades. This is not exactly how the load distribution of a wind load would act, but it is a close approximation. See Figure 7.4 for how the models deflect during wind load.

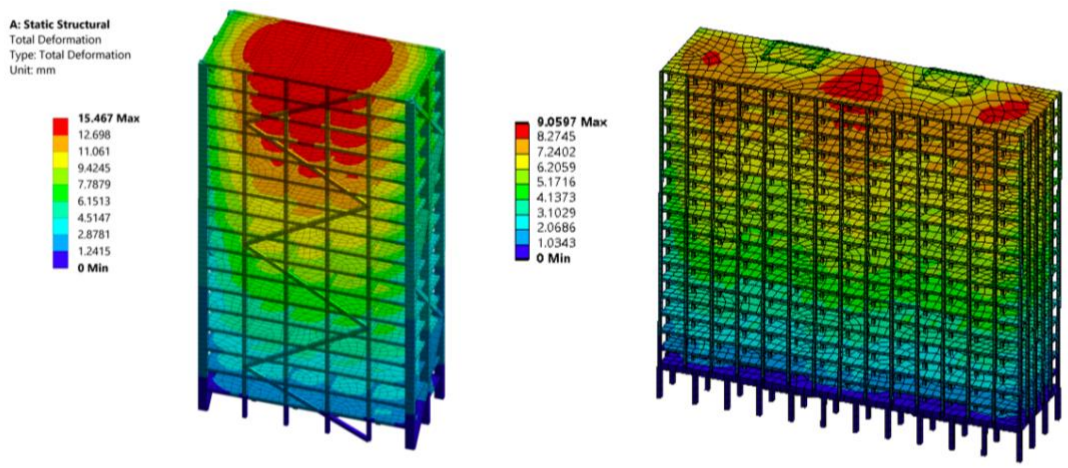


Figure 7.3 Deflection from gravity load for Mjøstårnet (left) and Brock Commons (right).

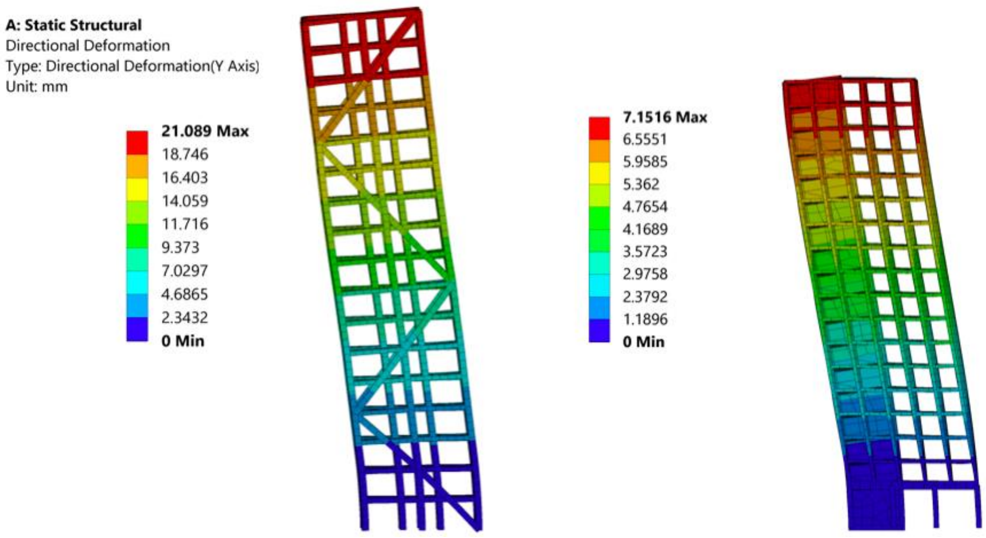


Figure 7.4 Lateral drift for Mjøstårnet (left) and Brock Commons (right) from wind load along the long side.

7.2 Simplifications

The two models based on Mjøstårnet and Brock Commons are simplified of how the two buildings are in real life. The complexity of timber, time restraints, and limitation in computing are reasons why simplifications were necessary. One of the most considerable simplifications was for the connections between the elements. Without proper knowledge of how each element is connected, it is impossible to get an accurate model of how rigid, elastic, and stiff the connections truly are. Therefore, the decision was made to make all the connections in the models rigid. Of course, this is not accurate to how they act in real life and is not suitable for in-depth analyses of the buildings. However, this was deemed a reasonable choice for these models, where only initial analyses would be performed for comparison and discussion.

Where dimensions of different structural members could not be found in the literature, were they estimated with the help of pictures or videos of the building. These analyses do not consider the load-carrying capacity of both structural elements and connections.

No complete dynamic behavior analyses will be performed on the models. The linear approximation will be used instead to get an understanding, even though it does not truly reflect the dynamic behavior of the models.

7.3 Frequency Analysis

The frequency analysis was performed for the two models with the help of *ANSYS* to determine the natural frequencies and periods of the models. The lowest natural frequency and period computed from the *ANSYS* simulation are compared to calculated results by hand, see Table 7.1, and are very similar.

Table 7.1 Fundamental natural frequency and period based on the Ansys models and hand calculations.

Building	Mjøstårnet		Brock Commons	
Method	ANSYS	Calculated	ANSYS	Calculated
f_i, Hz	0.64	0.63	1.03	1.02
T_i, s	1.56	1.6	0.97	0.98

The amount of modes used in the *ANSYS* analysis is determined with the help of the effective mass percentage participated in the analysis. At least 90 % of the effective mass needed to participate in the analysis for the result to be good enough. This meant that 20 modes were used for the model of Mjøstårnet, whereas 35 modes were used for the model of Brock Commons. The first three mode shapes of the models can be found in Figure 7.5 for Mjøstårnet and Figure 7.6 for Brock Commons.

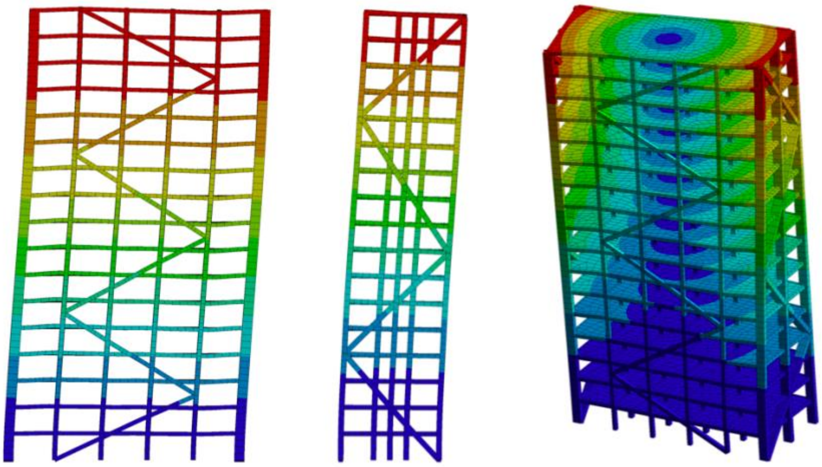


Figure 7.5 Visualization of the three first modes of Mjøstårnet

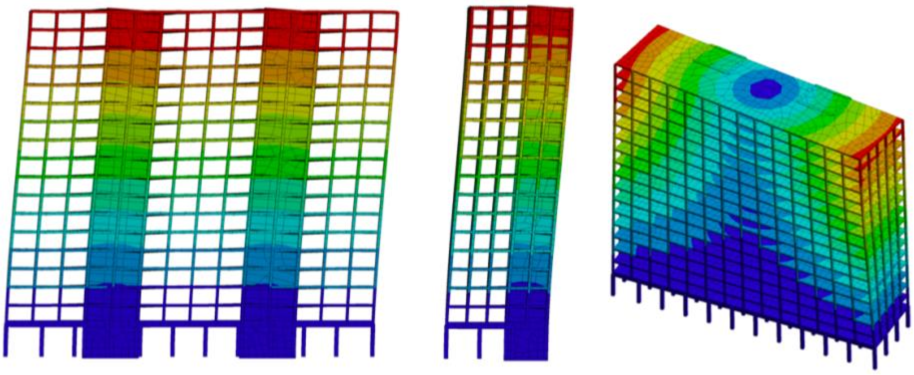


Figure 7.6 Visualization of the three first modes of Brock Commons

7.4 Lateral Load Analysis

The lateral load analysis is performed to understand better how the lateral loads in Vancouver affect the buildings. The dynamic procedure is needed according to NBCC for buildings with a natural frequency between 0.25-1 Hz. With the help of the Rayleigh method, which is based on the deformation under static wind load, was the frequencies for the two models calculated to be 0.7 Hz for Mjøstårnet and 1.1 Hz for Brock Commons. Deformations caused by the static wind load are given from *ANSYS*.

Figure 7.7 shows the lateral drift displayed for the two models when the wind is directed towards the long side. Here, it can be seen that for Mjøstårnet that the dynamic procedure is more critical than the static procedure. The dynamic procedure was not needed for Brock Commons as the static procedure is more critical. The inter-story drift does not exceed the limit from NBCC of $h_i/500$ (8 mm for Mjøstårnet and 5.6 mm for Brock Commons). See Appendix B for the drift of each story.

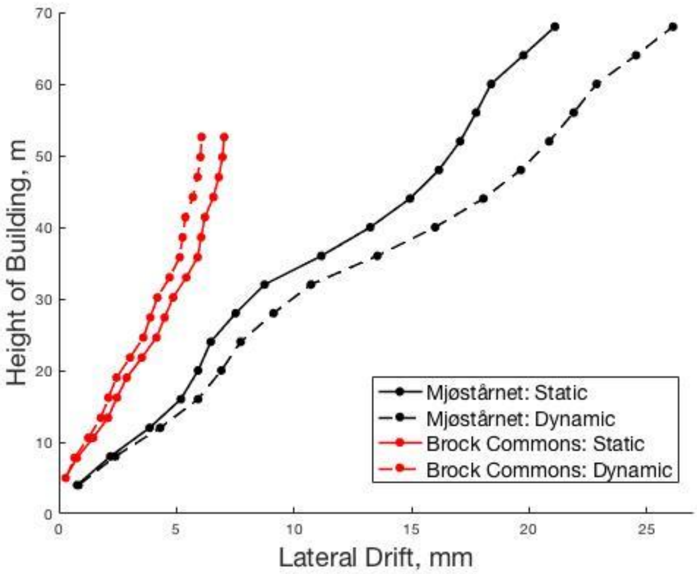


Figure 7.7 Graf of lateral drift caused by wind.

The Equivalent Static Force Procedure was used to calculate the lateral forces that affect the building, see Appendix B. The base shear force and base moment caused by seismic loads can be found in Table 7.2. The table shows that base shear is similar between the two models, but the base moment is almost twice as high for Mjøstårnet compared to Brock Commons.

Table 7.2 Base shear and moment from the seismic load.

Load	Base Shear, MN	Base Moment, MNm
Mjøstårnet	10.1	499
Brock Commons	9.1	252

7.5 Vibration Analysis

With both models being lightweight structures, it is required according to the national building code of Canada to check wind vibration serviceability. The results from the calculations can be found in Table 7.3. Based on these, neither of the models is sufficient for the 1.5 % of the acceleration of gravity (g) limit for residential buildings or the 2.5 % for office buildings. The peak acceleration along wind acceleration is too high.

Table 7.3 Peak acceleration in across- and along- wind direction.

Peak acceleration	a_w, % of g	a_d, % of g
Mjøstårnet	0.38	7.6
Brock Commons	0.03	3.9

7.6 Response Spectrum Analysis

A response spectrum analysis (RSA) is a linear-dynamic statistical analysis that looks at the natural modes of a building to indicate the likely maximum seismic response of a structure. This give gives insight into how the buildings handle dynamic behavior by using acceleration, velocity, or displacement as a function of the structural period for given time history and level of period. For the two models is the spectral acceleration used for Vancouver, see Figure 7.8, together with the modes with corresponding natural periods from the frequency analysis.

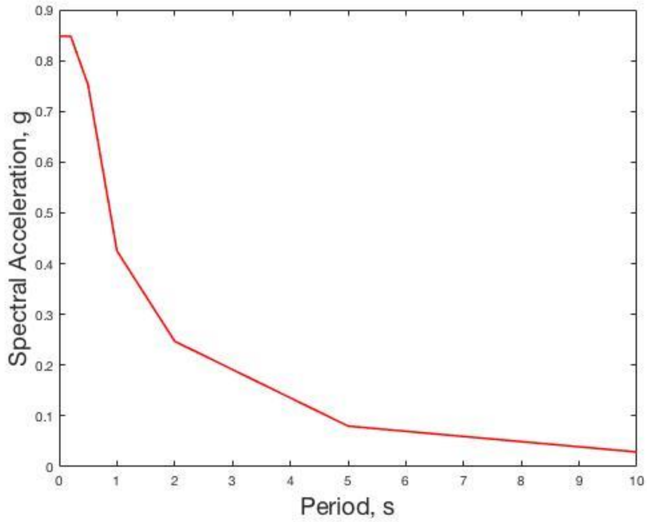


Figure 7.8 Design spectral acceleration of Vancouver City Hall.

Since the response spectrum analysis is a linear elastic analysis, is the results multiplied with R_dR_o / I_e to give a more realistic value of the anticipated deflections. R_d is the ductility-related force modificatory, and R_o is the overstrength-related force modification factor. For Mjøstårnet, is R_d chosen as 2 and R_o as 1.5, and for Brock Commons, is R_d chosen as 2 and R_o as 1.4. This is in accordance with NBCC for braced systems in timber that are moderately ductile, which is the structural system for Mjøstårnet, and moderately ductile shear walls in concrete, which is how the concrete cores in Brock Commons are designed. The importance factor I_e, is taken as 1 for the normal importance category.

The results from the Response spectrum analysis can be found in Figure 7.9, where the acceleration is along the long side, and figure 7.10, where it is along the short side. It is visible in these graphs that the models have a similar resistance when the acceleration is along the long side, as seen in Figure 7.9 are the lines are almost parallel. However, when the acceleration is along the short side is the performance of Mjøstårnet a lot worse than Brock Commons by having a lateral deflection almost twice as high.

The inter-story drift should not exceed 2.5 % of the story height because if it exceeds, is that an indicator of a bad seismic design. For Mjøstårnet is 2.5 % of the story height 100 mm, and for Brock Commons, it is 71 mm. None of the models exceed these numbers, with the highest deflection for Mjøstårnet being 55 mm and 32 mm for Brock Commons.

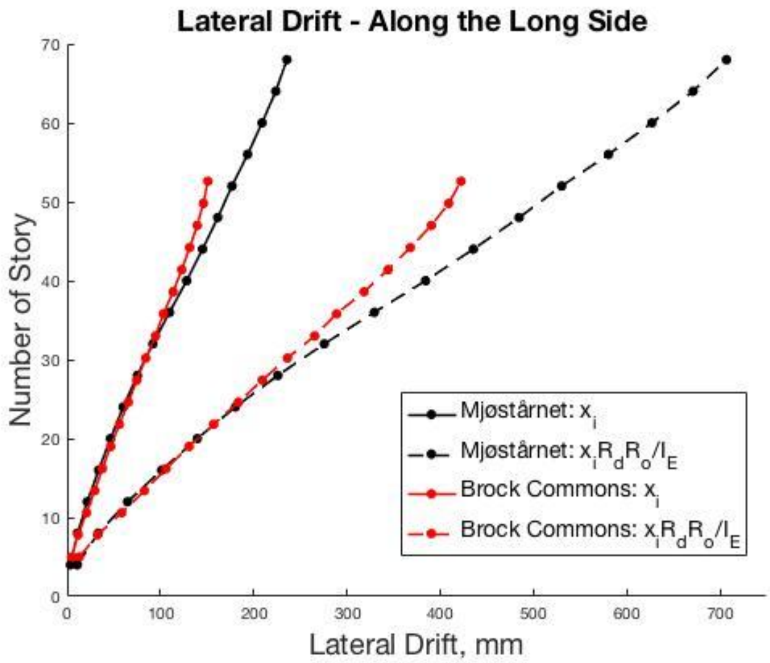


Figure 7.9 Lateral deformation along the long side of the building under earthquake.

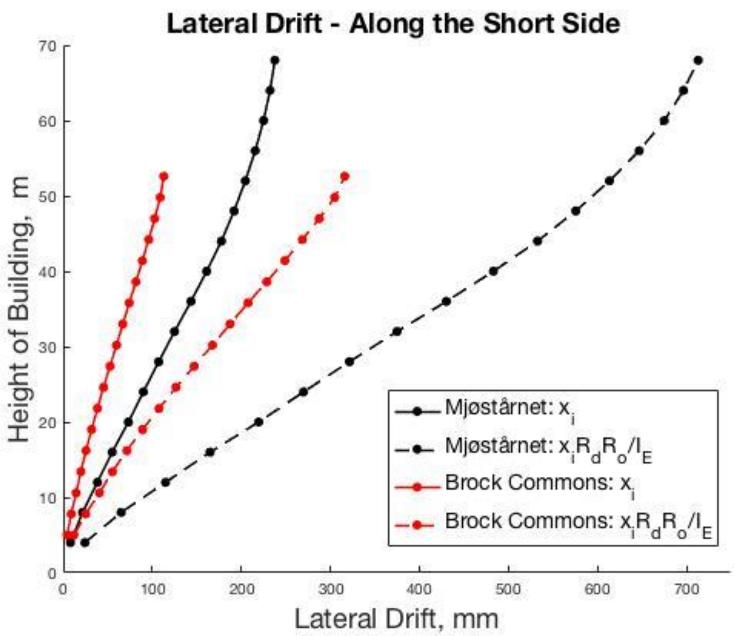


Figure 7.10 Lateral deformation along the short side of the building under earthquake.

7.7 Discussion

The computational limitation of not having connections representing the reality of these two buildings makes it very hard to be confident in the results. Therefore, the results are only a tool to compare the two models and their structural systems. What can be sure is that in reality, both Brock Commons and Mjøstårnet were designed for wind load, but only Brock Commons was designed for seismic load.

There is some reasoning that can be made from the results. First, the model of Mjøstårnet is performing worse than the one of Brock Commons, especially when it comes to withstanding lateral loads. This might not be so shocking when looking at the structural systems used for the two models, where Brock Commons has two concrete cores that act as stabilizing elements for the model. However, both models have similar results from the response spectrum analysis along the long side. This indicates that the structural system used in Mjøstårnet can be a viable option for seismic design. However, it might not be entirely suitable for a building with the exact dimensions and conditions as Mjøstårnet, which was marginally worse seen in the drift along the short side.

The model representing Brock Commons also performs better when it comes to wind-induced vibration of the building. The peak acceleration is higher in both the across – and along-wind direction for the Mjøstårnet model. The concrete cores in Brock Commons help with the vibration issue by increasing the stiffness and the lowest fundamental frequency. We know from Moelven's report that Mjøstårnet has vibration-related issues on the upper floors. Making the elevator shafts in concrete, like it is in Brock Commons, would help with these problems.

The results from the analyses indicate the limitations of pure timber systems compared to hybrid ones. Using a pure timber structure makes it harder to comply with the building code, and it would be more efficient to opt for a hybrid solution instead. Hybrid solutions use materials to their best ability, keep most structural elements in timber, and make it easier to comply with code. For example, suppose tall timber buildings would be to go even higher than Mjøstårnet and without having trouble with the serviceability limits, something that Mjøstårnet already has. In that case, it would be necessary to go for hybrid solutions like Brock Commons.

These analyses are only performed on two types of structural systems, and potentially, could another pure timber system outperform both of the systems used for Mjøstårnet and Bock Commons. However, it is unlikely that a pure timber structure would outperform a hybrid solution structurally.

8 Conclusions

This thesis was divided into three parts: a literature study, a questionnaire, and a computer modeling. These parts aimed to investigate the differences and similarities in the design process, codes, and guidelines for tall timbers in Scandinavia and Canada. Following are the conclusions that could be made for each part.

8.1 Literature study

It was clear from the literature study that the building code and practice are similar in Scandinavia and Canada, but there are still differences. The building practice and codes for fire, acoustics, and vibration were studied and compared between the two areas. Fire design in Scandinavia is more performance-based than in Canada. In Canada, timber is considered a combustible material and is therefore forced to encapsulate elements to create a code-accepted fire design. In Scandinavia, it is more common to see visible timber elements where the codes can be complied with the help of, for example, calculating the charring of the elements and using fire retardant paint. The design criteria for both vibration and acoustics are similar in Scandinavia and Canada, with just slight differences.

Companies in both Scandinavia and Canada have created structural systems in timber to make the choice of timber more accessible. No system is the same as the other and gives a good selection depending on how the building will be used and its circumstances. This makes the timber more accessible as an element in structural systems and is a good step to making it more a norm to use.

8.2 Questionnaire

The answers given from experts in both Scandinavia and Canada gave a good understanding of what is similar and different when designing tall timber buildings in these two places. Both agree that the main obstacles are connected to the serviceability use of the tall timber buildings and fire design, while the structural limitations were easier to comply with in comparison. Seismic loads are a concern in Canada, but it is something tall timber buildings can be designed for with not too much struggle.

The experts thought that the building code and practice for tall timber buildings are somewhat lacking, especially for fire design, where experts in Canada want it to be more performance-based. Experts in Scandinavia thought it should be clearer to avoid discussion and debate.

The experts also point out how the dynamic design is more complex than many other design phases.

The experts from Canada and Scandinavia also think there is an upgoing trend for timber in tall buildings. Around 10-25 % of the taller buildings will be in timber in 20 years.

8.3 Computer modeling

From comparing the model of Mjøstårnet with Brock Commons' model, several conclusions could be drawn. First, Brock Commons is a more conservative design compared to Mjøstårnet, mainly because of having two stabilizing concrete cores and the need to be designed for seismic loads. Second, results from the response spectrum analysis show how depending on the direction of the acceleration, Mjøstårnet can perform similarly to Brock Common, but not in all directions. This indicates that the structural model used in Mjøstårnet can be used for seismic design but that it is very situational and depends on the shape of the building.

It can also be shown from the analyses the effect of using concrete cores as stabilizing units and how much better it performs in wind loads compared to an all timber system like the one used in Mjøstårnet. Pure timber buildings start having more design problems the higher they become, as seen in the Mjøstårnet - model. Therefore, hybrid systems are a good solution to utilize each material for its best properties and thus have it easier to comply with design codes and create taller buildings where most of the building material is still timber.

9 Further Research

The topic of this thesis is vast, and there is a lot that can be done to help the future of timber in tall timber buildings. Following are some recommendations for further research that could be beneficial for the future use of timber.

- Investigate when it is better to use a hybrid solution compared to an all-timber building from a structural, economic, and life cycle perspective.
- Continue research on fire design for timber buildings to help the development of new building standards and practices. Examples of topics could be testing further timber products fire resistance, the effect of sprinkler systems, and the strength of connections in case of a fire.
- Continue optimizing structural systems in timber to make it more accessible.
- Investigate different approaches to minimize the effect of wind-induced vibrations on timber buildings.

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Appendix A

Tidstämpel	In what area do you live?	How long have you worked with timber structures professionally?	How many of todays new tall buildings (>25 m) in your country of residency use timber as part of their main structural system?	In 20 years, how	What are the main obstacles when it comes to designing tall timber buildings?	Is there any part(s) of the design code/building practice when it comes to tall timber buildings that are easier or harder to satisfy?
2022/02/22 3:30:30 em GMT−7	Canada	Finished PhD by 2019. Started working after that.	5-10 %	10-25 %	Limitations when it comes to code.	Canada east coast, wind is governing. West coast, seismic load. Fire, acoustics and vibrations are main issue. Height limitation has been a big limitation, happy that it is up to 12 storeys now.
2022/03/07 11:24:57 fm GMT−7	Canada	30 years	< 5 %	< 5 %	Technology and code approvals for fire	Structure approval is easier than fire.
2022/03/07 11:57:37 fm GMT−7	Canada	25 years	< 5 %	10-25 %	Building codes and perception of developers, insurance and financial institutions	Fire and life safety provisions (Part 3) of the NBCC
2022/03/08 12:48:49 fm GMT−7	Canada	26 years	< 5 %	10-25 %	everyone is inventing the wheel over and over again. But that is normal and will take time. So sharing of information and experience is the most imporant	wind performance, waht are the real drifts, vertical settlemnt of the system, seimic design
2022/03/09 10:21:14 fm GMT−7	Canada	14 years	< 5 %	5-10 %	cost, jurisdictional fire rating concerns	fire rating (particularly for exposed structures), timber lateral systems (generally hybrid systems are used)
2022/04/06 12:22:01 fm GMT−6	Scandinavia	25 years	< 5 %	5-10 %	Lack of experience (and therefore knowledge) among all partners regarding tall (>25 m, 8 stories) buildings	Fire regulations and design for wind loads in serviceability limit state.
2022/04/12 2:03:25 fm GMT−6	Scandinavia	17 years	< 5 %	> 50%	Technological knowledge, I would say, although it is not easy to answer as they are many other obstacles (traditions, conflicts of interests). So we need both education to spread what we know and research to find what we don't know. From my point of view the most interesting and challenging obstacle is the wind-induced vibrations at the top of tall timber buildings. But timber experts on acoustic, fire, moisture would have another answer ;)	Comparing to small timber buildings and to tall traditional buildings, it is harder to achieve good comfort for wind-induced vibrations at the top of tall timber buildings. Comparing to only tall traditional buildings it will be easier to fulfil the coming environmental declaration and threshold (to be in place in 2027 in Sweden) for timber buildings in general.
2022/04/26 12:00:51 em GMT−6	Scandinavia	22 Years	5-10 %	10-25 %	Uncertainty concerning e.g. dynamic behaviour, long-term behaviour. And last, but not least, lack of knowledge- by several contractors - concerning	harder: vibrational behaviour when wind is blowing (related to the SLS)and somewhat also the acoustics
2022/04/26 11:44:31 em GMT−6	Scandinavia	25 years	< 5 %	10-25 %	knowledge and experiences	Hard: dynamic behavior Easy: USL-design
2022/04/27 3:18:39 fm GMT−6	Scandinavia	8 years	5-10 %	10-25 %	Economy (cost of material, land and loss of income (less space to sell or rent within given footprint)), also Fire-regulations and lack of guidance with regards to dynamic response to wind in tall timber buildings	Lack of design code/building practice with regards to CLT is a problem in and of itself, otherwise the design code with regards to dynamic response to wind is quite difficult to achieve. Vibration in floor-slabs is another quite hard thing to design for without hurting the economy of the project. ULS designing, buckling of walls etc I would say are not too difficult to satisfy.
Tidstämpel	**In what area do you live?**	**How long have you worked with timber structures professionally?**	**How many of todays new tall buildings (>25 m) in your country of residency use timber as part of their**	**In 20 years, how**	**What are the main obstacles when it comes to designing tall timber buildings?**	**Is there any part(s) of the design code/building practice when it comes to tall timber buildings that are easier or harder to satisfy?**

Is there any part(s) of the design code/building practice when it comes to tall timber buildings that is easier or harder to understand? Or is everything at the same level of complexity?	At what part of the design or construction phase is more effort needed? Where is it less needed?	Do you have any additional insight on the design process of tall timber structures that you want to share?
It all depends on the level of experience. Couldn't say that any part is more complex than another. What is available is clear.	Having a clear concept is the most important thing. A good concept and a good design sets the tone of the rest of the project. After that is it just good communication and continued planning that creates a good project.	Wood first act --> Government act in BC, should consider wood first if applicable.
Same level of complexity	More effort is required at early design stages.	It's an evolving field and will take time for adoption.
Fire and life safety provisions (Part 3) of the NBCC and perhaps Part 4 as well on seismic design.	Fire protection and seismic design are the key areas in terms of design. For construction Phase, it's moisture and water management and potential fire risks during construction	Transitioning the building codes in Canada to become more performance based would facilitate and support the design and approval of tall wood buildings.
not quite sure i understand the question,	design phase needs more time, and suppliers need to be endaged early. but a lot of owners dont like that as they feel (sometimes rightfully so) the cant get out of it once the suppliers are on board.	
similar level	cost estimating, code consultant and fire engineering, design and fabrication coordination	
Fire regulations (open for debate and discussions)	Necessary for all types of competences to be involved from the beginning of the process. This to insure that no aspect is forgotten that has a large effect on the final design.	
Yes, they are some parts that are more easier or harder to understand and to apply.	I would say the control and inspection parts at different stage of the whole process. In Sweden it is almost none.	About question 3, I don't really know, it is just a fair guess. About question 4, it is only a dream! Although the number of tall buildings (>25 m or > 8 storeys) will be still rather small compared to the number of lower buildings!
Wind induced vibration might be an issue	In the construction effort is needed to protect the wood from moisture	
Hard: dynamic behavior and fire	More: dynamic behavior (damping) and fire Less: USL-design	
Dynamic response with regards to wind in the latest EKS (Sweden) is contradicting itself which is a problem. Also a number of design principles for tall buildings in the EC is not developed/meant for tall buildings with lightweight structure (timber) so it is a challenge for the designer to judge if structural performance while designing is "on the safe side"	Design phase; early on to decide if a timber structure is actually feasible and the best choice for a project. Construction phase; assembly on site to make sure connections are executed correctly.	Question the reason to use timber for tall structures; is that where timber is used to it's best potential? In a time when each material is a scarce resource, are tall timber buildings material-effective?
Is there any part(s) of the design code/building practice when it comes to tall timber buildings that is easier or harder to understand? Or is everything at the same level of complexity?	**At what part of the design or construction phase is more effort needed? Where is it less needed?**	**Do you have any additional insight on the design process of tall timber structures that you want to share?**

Appendix B

Load Calculations Mjøstårnet

Building Data

Area: Vancouver City Hall		
Height building	68	m
Area floor	525	m2

Weight of Elements

Concrete floors	7,2	kPa
Timber floors	2	kPa
Inner beams concrete	138,2	kN/floor
Outer beams concrete	737,7	kN/floor
Inner beams wood	82,8	kN/floor
Outer beams wood	466,2	kN/floor
Inner column	91,1	kN/floor
Outer column	76,4	kN/floor
Corner column	93,3	kN/floor
Braces	64,5	kN/floor
Roof	260,9	kN
Partition walls	0,5	kPa

Dead Load

Story		
Roof	5505	kN
16	5244	kN
15	5244	kN
14	5244	kN
13	5244	kN
12	5244	kN
11	5244	kN
10	2122	kN
9	2122	kN
8	2122	kN
7	2122	kN
6	2122	kN
5	2122	kN
4	2122	kN
3	2122	kN
2	2122	kN
1	2122	kN

Wind Load: Static Analysis (Section 4,1,7 NBCC 2015)

I_w	1
q	0,45
C_t	1
C_g	2
C_p	0,8
A_floor	140

Wind Load, Long Side

Story	h_i, m	W,i	C_e	F_i, kN	V_i, kN
17	68	550	1,18	59,4	59,4
16	64	524	1,16	116,6	176,0
15	60	524	1,13	114,4	290,3
14	56	524	1,11	112,0	402,3
13	52	524	1,09	109,5	511,9
12	48	524	1,06	106,9	618,8
11	44	524	1,03	104,2	723,0
10	40	212	1,00	101,3	824,3
9	36	212	0,97	98,1	922,4
8	32	212	0,94	94,7	1017,1
7	28	212	0,90	91,0	1108,1
6	24	212	0,86	86,9	1194,9
5	20	212	0,82	82,2	1277,2
4	16	212	0,76	76,9	1354,1
3	12	212	0,7	70,6	1424,6
2	8	212	0,7	70,6	1495,2
1	4	212	0,7	70,6	1565,8

Deflection Long Side (From ANSYS Model)

Story	h_i, m	x_i, mm	X_i, mm	Fixi, mm2	Wixi^2, tmm2
17	68	1,34	21,09	80	988
16	64	1,37	19,75	160	984
15	60	0,64	18,38	73	215
14	56	0,68	17,74	76	242
13	52	0,9	17,06	99	425
12	48	1,23	16,16	132	793
11	44	1,69	14,93	176	1498
10	40	2,08	13,24	211	918
9	36	2,41	11,16	236	1233
8	32	1,23	8,75	116	321
7	28	1,06	7,52	96	238
6	24	0,54	6,46	47	62
5	20	0,73	5,92	60	113
4	16	1,33	5,19	102	375
3	12	1,67	3,86	118	592
2	8	1,41	2,19	99	422
1	4	0,78	0,78	55	129
			Sum	1936	9549

A_floor	60

Wind Load, Short Side

Story	h_i, m	W,i	C_e	F_i, kN	V_i, kN
17	68	550	1,18	25,4	25,4
16	64	524	1,16	50,0	75,4
15	60	524	1,13	49,0	124,4
14	56	524	1,11	48,0	172,4
13	52	524	1,09	46,9	219,4
12	48	524	1,06	45,8	265,2
11	44	524	1,03	44,7	309,9
10	40	212	1,00	43,4	353,3
9	36	212	0,97	42,0	395,3
8	32	212	0,94	40,6	435,9
7	28	212	0,90	39,0	474,9
6	24	212	0,86	37,2	512,1
5	20	212	0,82	35,2	547,4
4	16	212	0,76	33,0	580,3
3	12	212	0,7	30,2	610,6
2	8	212	0,7	30,2	640,8
1	4	212	0,7	30,2	671,0

Deflection Short Side From ANSYS Model)

Story	h_i, m	x_i, mm	X_i, mm	Fixi, mm2	Wixi^2, tmm2
17	68	0,35	10,01	9	67
16	64	0,26	9,66	13	35
15	60	0,12	9,4	6	8
14	56	0,45	9,28	22	106
13	52	0,44	8,83	21	102
12	48	0,63	8,39	29	208
11	44	0,52	7,76	23	142
10	40	0,41	7,24	18	36
9	36	0,54	6,83	23	62
8	32	0,73	6,29	30	113
7	28	0,91	5,56	35	176
6	24	1,07	4,65	40	243
5	20	0,51	3,58	18	55
4	16	0,79	3,07	26	132
3	12	0,58	2,28	18	71
2	8	1,09	1,7	33	252
1	4	0,61	0,61	18	79
			Sum	381	1888

Calculating the Lowest Natural Frequency (Using Rayleigh's Method)

f_n_long	0,7166911	f_n_short	0,71459796

Dynamic Wind Load (Section 4,1,7,8 NBCC 2015)

K	0,1	Rough Terrain
T	3600	sek
H	68	m
w	35	m
w/H	0,51	
B	0,82	
f_n	0,7166911	Hz
beta	0,019	From Moelven's raport
I_w	1	
rho	1,2929	kg/m3
q	450	Pa
V	26,4	m/s
CeH	1,16	
V_H	28,4	m/s
x_0	30,8	
F	0,102	
s	0,0190762	
v	0,2383947	
sigma/u	0,2822981	
g_p	3,8325406	
c_g	2,0819188	

Check Slenderness Around Both Axes

0,352505823 > 1/3, not slender around both axes

Dynamic Wind Load and Deflection from Ansys

Story	h_i, m	C_e	P_i, kN	V_i, kN	x_i, mm	X_i, mm
17	68	1,16	60,7	60,7	1,57	26,11
16	64	1,12	117,8	178,5	1,68	24,54
15	60	1,09	114,0	292,5	0,97	22,86
14	56	1,05	110,2	402,7	1,04	21,89
13	52	1,01	106,2	508,8	1,21	20,85
12	48	0,97	102,0	610,8	1,59	19,64
11	44	0,93	97,7	708,5	2,05	18,05
10	40	0,89	93,1	801,6	2,46	16
9	36	0,84	88,3	889,9	2,82	13,54
8	32	0,79	83,3	973,2	1,59	10,72
7	28	0,74	77,9	1051,1	1,4	9,13
6	24	0,69	72,1	1123,2	0,82	7,73
5	20	0,63	65,8	1189,1	0,99	6,91
4	16	0,56	58,9	1248,0	1,61	5,92
3	12	0,50	52,5	1300,4	1,91	4,31
2	8	0,50	52,5	1352,9	1,56	2,4
1	4	0,50	52,5	1405,3	0,84	0,84

Seismic Load (Section 4,1,8, NBCC 2015)

Spectral Accelerations (table C-3 NBCC 2015)

S_a(0,2)	0,848
S_a(0,5)	0,751
S_a(1,0)	0,425
S_a(2,0)	0,257
S_a(5,0)	0,08
S_a(10,0)	0,029
PGA	0,369
PGV	0,553

S(0,2)/S(5,0)	10,6	
M_v	1	
I_E	1	
W	58191	kN
h_n	64	
T_a	1,6	
S(T_a)	0,8157	
R_dR_o	3	
J	0,9	

V	15822,146	kN
F_t	3955,5364	kN

Seismic Load per Story

Story	W_i, t	h_i,t	Wihi, t,m	Wihi/sum t,	F_i, kN	V_i
17	550	68	37432	0,147	1749	1749
16	524	64	33560	0,132	1568	1568
15	524	60	31463	0,124	1470	3038
14	524	56	29365	0,116	1372	4409
13	524	52	27268	0,107	1274	5683
12	524	48	25170	0,099	1176	6859
11	524	44	23073	0,091	1078	7937
10	212	40	8489	0,033	397	8333
9	212	36	7640	0,030	357	8690
8	212	32	6792	0,027	317	9008
7	212	28	5943	0,023	278	9285
6	212	24	5094	0,020	238	9523
5	212	20	4245	0,017	198	9721
4	212	16	3396	0,013	159	9880
3	212	12	2547	0,010	119	9999
2	212	8	1698	0,007	79	10078
1	212	4	849	0,003	40	10118
sum	5819		254023	0,99665802		

Moments Created by Seismic Load

Story	h_i,t	Jx	Mi,1, kNm	M_1, kNm
17	68	1	118906	118906
16	64	1	100337	100337
15	60	1	88187	188524
14	56	1	76820	265344
13	52	1	66238	331582
12	48	1	56440	388022
11	44	1	47425	435447
10	40	1,002	15895	451341
9	36	1,01	13020	464362
8	32	1,03	10432	474794
7	28	1,05	8128	482922
6	24	1,07	6110	489032
5	20	1,10	4378	493411
4	16	1,16	2932	496342
3	12	1,24	1770	498112
2	8	1,41	895	499007
1	4	1,92	305	499312

Frequency Analysis (from Ansys)

Mode	f_i, Hz	T_i, s	Acc
1	0,64246	1,5565	3,1942
2	0,68356	1,4629	3,3575
3	1,1605	0,8617	5,0514
4	2,544	0,3931	7,7049
5	2,9378	0,3404	7,8701
6	3,8332	0,2609	8,1195
7	4,427	0,2259	8,2292
8	4,47	0,2237	8,236
9	4,6271	0,2161	8,2599
10	5,3164	0,1881	8,3104
11	5,9002	0,1695	8,3104
12	5,9822	0,1672	8,3104
13	6,4176	0,1558	8,3104
14	6,4242	0,1557	8,3104
15	6,6434	0,1505	8,3104
16	6,7513	0,1481	8,3104
17	7,0942	0,141	8,3104
18	8,0982	0,1235	8,3104
19	8,144	0,1228	8,3104
20	8,2753	0,1208	8,3104

Response Spectrum Analysis (from Ansys)

Direction	y			
story	X	x	XRoRd/Ie	xRoRd/Ie
17	235,64	11,93	706,92	35,79
16	223,71	14,71	671,13	44,13
15	209	15,5	627	46,5
14	193,5	16,75	580,5	50,25
13	176,75	15,21	530,25	45,63
12	161,54	16,33	484,62	48,99
11	145,21	17,09	435,63	51,27
10	128,12	18,32	384,36	54,96
9	109,8	17,89	329,4	53,67
8	91,91	16,61	275,73	49,83
7	75,3	15,17	225,9	45,51
6	60,13	13,59	180,39	40,77
5	46,54	12,77	139,62	38,31
4	33,77	12,14	101,31	36,42
3	21,63	10,5	64,89	31,5
2	11,13	7,5	33,39	22,5
1	3,63	3,63	10,89	10,89

Direction	x			
story	X	x	XRoRd/Ie	xRoRd/Ie
17	237,7	5,47	713,1	16,41
16	232,23	7,21	696,69	21,63
15	225,02	9,4	675,06	28,2
14	215,62	11,12	646,86	33,36
13	204,5	12,63	613,5	37,89
12	191,87	14,29	575,61	42,87
11	177,58	16,55	532,74	49,65
10	161,03	17,59	483,09	52,77
9	143,44	18,48	430,32	55,44
8	124,96	17,82	374,88	53,46
7	107,14	17,16	321,42	51,48
6	89,98	16,81	269,94	50,43
5	73,17	18,2	219,51	54,6
4	54,97	16,67	164,91	50,01
3	38,3	16,65	114,9	49,95
2	21,65	13,54	64,95	40,62
1	8,11	8,11	24,33	24,33

Load Calculations Brock Commons

Building Data

Area: Vancouver City Hall		
Height building	53	m
Area floor	840	m2

Weight of Elements

Concrete floor	24	kPa
Timber floors	2	kPa
Concrete on top of floor	1,2	kPa
ConcreteColumn	1728,0	kN/floor
TimberColumn	147,8	kN/floor
Concrete core	376,3	kN/floor
Partition walls	0,5	kPa

Dead load

Story		
18	3632	kN
17	3632	kN
16	3632	kN
15	3632	kN
14	3632	kN
13	3632	kN
12	3632	kN
11	3632	kN
10	3632	kN
9	3632	kN
8	3632	kN
7	3632	kN
6	3632	kN
5	3632	kN
4	3632	kN
3	3632	kN
2	3632	kN
1	21104	kN

Wind load: Static Analysis (Section 4,1,7 NBCC 2015)

I_w	1
q	0,45
C_t	1
C_g	2
C_p	0,8
A_floor	156,8
A_floor_bottor	280

Wind Load, Long Side

Story	h_i, m	W,i	C_e	F_i, kN	V_i, kN
18	52,6	363	1,0905	61,6	61,6
17	49,8	363	1,0728	121,1	182,7
16	47	363	1,0543	119,0	301,7
15	44,2	363	1,0351	116,9	418,6
14	41,4	363	1,0149	114,6	533,1
13	38,6	363	0,9938	112,2	645,3
12	35,8	363	0,9716	109,7	755,0
11	33	363	0,9482	107,0	862,1
10	30,2	363	0,9233	104,2	966,3
9	27,4	363	0,8967	101,2	1067,6
8	24,6	363	0,8682	98,0	1165,6
7	21,8	363	0,8373	94,5	1260,1
6	19	363	0,8035	90,7	1350,8
5	16,2	363	0,7659	86,5	1437,3
4	13,4	363	0,7236	81,7	1519,0
3	10,6	363	0,7	79,0	1598,0
2	7,8	363	0,7	79,0	1677,0
1	5	2110	0,7	141,1	1818,1

Deflection Long Side (From ANSYS Model)

Story	h_i, m	x_i, mm	X_i, mm	Fixi, mm2	WiXi^2, tmm2
18	52,6	0,07	7,03	4,309	2
17	49,8	0,16	6,96	19,378	9
16	47	0,23	6,8	27,377	19
15	44,2	0,36	6,57	42,068	47
14	41,4	0,16	6,21	18,333	9
13	38,6	0,15	6,05	16,830	8
12	35,8	0,48	5,9	52,654	84
11	33	0,56	5,42	59,947	114
10	30,2	0,36	4,86	37,526	47
9	27,4	0,35	4,5	35,434	44
8	24,6	0,62	4,15	60,771	140
7	21,8	0,64	3,53	60,498	149
6	19	0,42	2,89	38,098	64
5	16,2	0,38	2,47	32,859	52
4	13,4	0,63	2,09	51,463	144
3	10,6	0,69	1,46	54,529	173
2	7,8	0,48	0,77	37,933	84
1	5	0,29	0,29	40,925	177
			Sum	691	1367

A_floor_bottor	75	A_floor	42

Wind Load, Short Side

Story	h_i, m	W,i	C_e	F_i, kN	V_i, kN
18	52,6	363	1,0905	16,5	16,5
17	49,8	363	1,0728	32,4	48,9
16	47	363	1,0543	31,9	80,8
15	44,2	363	1,0351	31,3	112,1
14	41,4	363	1,0149	30,7	142,8
13	38,6	363	0,9938	30,1	172,9
12	35,8	363	0,9716	29,4	202,2
11	33	363	0,9482	28,7	230,9
10	30,2	363	0,9233	27,9	258,8
9	27,4	363	0,8967	27,1	286,0
8	24,6	363	0,8682	26,3	312,2
7	21,8	363	0,8373	25,3	337,5
6	19	363	0,8035	24,3	361,8
5	16,2	363	0,7659	23,2	385,0
4	13,4	363	0,7236	21,9	406,9
3	10,6	363	0,7	21,2	428,0
2	7,8	363	0,7	21,2	449,2
1	5	2110	0,7	37,8	487,0

Deflection Short Side From ANSYS Model)

Story	h_i, m	x_i, mm	X_i, mm	Fixi, mm2	WiXi^2, tmm2
18	52,6	0,11	2,24	1,814	4
17	49,8	0,12	2,13	3,893	5
16	47	0,1	2,01	3,188	4
15	44,2	0,08	1,91	2,504	2
14	41,4	0,11	1,83	3,376	4
13	38,6	0,12	1,72	3,606	5
12	35,8	0,11	1,6	3,232	4
11	33	0,16	1,49	4,588	9
10	30,2	0,12	1,33	3,350	5
9	27,4	0,1	1,21	2,712	4
8	24,6	0,2	1,11	5,251	15
7	21,8	0,23	0,91	5,824	19
6	19	0,07	0,68	1,701	2
5	16,2	0,05	0,61	1,158	1
4	13,4	0,17	0,56	3,720	10
3	10,6	0,17	0,39	3,599	10
2	7,8	0,14	0,22	2,964	7
1	5	0,08	0,08	3,024	14
			Sum	60	126

Calculating the Lowest Natural Frequency (Using Rayleigh's Method)

f_n	1,1314402		f_n_short	1,09453862

Dynamic Wind Load (Section 4,1,7,8 NBCC 2015)

K	0,1	Rough Terrain
T	3600	sek
H	53	m
w	56	m
w/H	1,06	
B	0,82	
f_n	1,1314402	Hz
beta	0,019	From Moelven's raport
I_w	1	
rho	1,2929	kg/m3
q	450	Pa
V	26,4	m/s
CeH	1,02	
V_H	26,6	m/s
x_0	51,9	
F	0,072	
s	0,0060234	
v	0,1860312	
sigma/u	0,2877912	
g_p	3,7673969	
c_g	2,0842238	

Check Slenderness Around Both Axes

0,546844406	> 1/3, not slender around both axes

Dynamic Wind Load and Deflection from Ansys

Story	h_i, m	C_e	P_i, kN	V_i, kN	x_i, mm	X_i, mm
18	52,6	1,02	59,9	59,9	0,05	6,07
17	49,8	0,99	116,5	176,3	0,12	6,02
16	47	0,96	113,2	289,5	0,2	5,9
15	44,2	0,93	109,7	399,3	0,32	5,7
14	41,4	0,90	106,2	505,5	0,12	5,38
13	38,6	0,87	102,6	608,0	0,12	5,26
12	35,8	0,84	98,8	706,8	0,43	5,14
11	33	0,81	94,8	801,6	0,52	4,71
10	30,2	0,77	90,7	892,3	0,3	4,19
9	27,4	0,73	86,4	978,7	0,3	3,89
8	24,6	0,70	81,9	1060,6	0,56	3,59
7	21,8	0,66	77,1	1137,7	0,58	3,03
6	19	0,61	72,0	1209,6	0,34	2,45
5	16,2	0,56	66,4	1276,1	0,32	2,11
4	13,4	0,51	60,4	1336,5	0,54	1,79
3	10,6	0,50	58,8	1395,3	0,58	1,25
2	7,8	0,50	58,8	1454,1	0,38	0,67
1	5	0,50	105,0	1559,2	0,29	0,29

Seismic Load (Section 4,1,8, NBCC 2015)

Spectral Accelerations (table C-3 NBCC 2015)

S_a(0,2)	0,848
S_a(0,5)	0,751
S_a(1,0)	0,425
S_a(2,0)	0,257
S_a(5,0)	0,08
S_a(10,0)	0,029
PGA	0,369
PGV	0,553

S(0,2)/S(5,0)	10,6	
M_v	1	
I_E	1	
W	82849	kN
h_n	53	
T_a	0,9821479	
S(T_a)	0,438	
R_dR_o	3	
J	0,96	

V	12095,993	kN
F_t	3023,9983	kN

Seismic Load per Story

Story	W_i, t	h_i,t	Wihi, t,m	Wihi/sum t,	F_i, kN	V_i
18	363	52,6	19105	0,097	880	880
17	363	49,8	18088	0,092	833	1713
16	363	47	17071	0,087	786	2499
15	363	44,2	16054	0,081	739	3238
14	363	41,4	15037	0,076	692	3930
13	363	38,6	14020	0,071	646	4576
12	363	35,8	13003	0,066	599	5174
11	363	33	11986	0,061	552	5726
10	363	30,2	10969	0,056	505	6231
9	363	27,4	9952	0,051	458	6690
8	363	24,6	8935	0,045	411	7101
7	363	21,8	7918	0,040	365	7466
6	363	19	6901	0,035	318	7783
5	363	16,2	5884	0,030	271	8054
4	363	13,4	4867	0,025	224	8278
3	363	10,6	3850	0,020	177	8456
2	363	7,8	2833	0,014	130	8586
1	2110	5	10552	0,054	486	9072
sum	8285		197023	1,000		

Moments Created by Seismic Load

Story	h_i,t	Jx	Mi,1, kNm	M_1, kNm
17	64	1	39144	39144
16	60	1	34743	73887
15	56	1	30603	104490
14	52	1,0057	26878	131368
13	48	1,014	23433	154801
12	44	1,0236	20225	175026
11	40	1,0351	17252	192278
10	36	1,05	14516	206794
9	32	1,07	12015	218809
8	28	1,09	9750	228559
7	24	1,11	7722	236281
6	20	1,15	5929	242210
5	16	1,20	4373	246583
4	12	1,28	3052	249636
3	8	1,42	1968	251603
2	4	1,72	1119	252722

Frequency Analysis (from Ansys)

Mode	f_i, Hz	T_i, s	Acceleration
1	1,031	0,9699	4,3577
2	1,0937	0,9143	4,7141
3	1,4165	0,706	6,0495
4	3,4418	0,2905	8,0264
5	3,6125	0,2768	8,0695
6	3,9739	0,2516	8,1485
7	5,0268	0,1989	8,3104
8	5,0899	0,1965	8,3104
9	5,4623	0,1831	8,3104
10	5,4855	0,1823	8,3104
11	6,142	0,1628	8,3104
12	6,4452	0,1552	8,3104
13	6,5621	0,1524	8,3104
14	6,9915	0,143	8,3104
15	7,3091	0,1368	8,3104
16	7,341	0,1362	8,3104
17	7,4697	0,1339	8,3104
18	7,643	0,1308	8,3104
19	7,8549	0,1273	8,3104
20	8,1199	0,1232	8,3104
21	8,1834	0,1222	8,3104
22	8,3542	0,1197	8,3104
23	8,4831	0,1179	8,3104
24	8,5484	0,117	8,3104
25	8,6757	0,1153	8,3104
26	8,8151	0,1134	8,3104
27	8,849	0,113	8,3104
28	8,8822	0,1126	8,3104
29	9,0343	0,1107	8,3104
30	9,1606	0,1092	8,3104
31	9,5134	0,1051	8,3104
32	9,6202	0,1039	8,3104
33	9,6605	0,1035	8,3104
34	9,8523	0,1015	8,3104
35	9,8699	0,1013	8,3104

Response Spectrum Analysis (from Ansys)

Direction	y			
Story	X	x	XRdRo/Ie	xRdRo/Ie
18	150,8	4,7	452,4	13,2
17	146,1	6,6	438,3	18,5
16	139,5	8,1	418,5	22,7
15	131,4	8,5	394,2	23,8
14	122,9	9,2	368,7	25,8
13	113,7	10,5	341,1	29,4
12	103,2	8,4	309,6	23,5
11	94,8	10,4	284,4	29,1
10	84,4	9,7	253,2	27,2
9	74,7	9,1	224,1	25,5
8	65,6	9,5	196,8	26,6
7	56,1	9,4	168,3	26,3
6	46,7	8,8	140,1	24,6
5	37,9	8,3	113,7	23,2
4	29,6	8,7	88,8	24,4
3	20,9	9,2	62,7	25,8
2	11,7	7	35,1	19,6
1	4,7	4,7	14,1	13,2

Direction	x			
Story	X	x	XRdRo/Ie	xRdRo/Ie
18	112,9	4	316,12	11,2
17	108,9	6,2	304,92	17,36
16	102,7	6,8	287,56	19,04
15	95,9	7	268,52	19,6
14	88,9	7,3	248,92	20,44
13	81,6	7,5	228,48	21
12	74,1	7,2	207,48	20,16
11	66,9	7	187,32	19,6
10	59,9	7,4	167,72	20,72
9	52,5	7,3	147	20,44
8	45,2	6,8	126,56	19,04
7	38,4	6,6	107,52	18,48
6	31,8	6,3	89,04	17,64
5	25,5	5,8	71,4	16,24
4	19,7	5,2	55,16	14,56
3	14,5	5,5	40,6	15,4
2	9	4,7	25,2	13,16
1	4,3	4,3	12,04	12,04

Vibration Analysis Mjøstårnet and Brock Commons

Mjøstårnet				Brock Commons		
a_w	0,0370968	0,3782	a_w	0,00252008	0,025688921
a_d	0,7457809	7,6023	a_d	0,38049666	3,878661127
f_nw	0,714598		f_nw	1,09453862	
f_nd	0,7166911		f_nd	1,13144017	
gp	3,8325406		gp	3,76739687	
w	35	m	w	56	
d	15	m	d	15	
a_r	0,4820624		a_r	0,04397845	
V_H	28,4		V_H	26,6	
rho_B	485	kg/m3	rho_B	1900	
g	9,81	m/s2	g	9,81	
beta_w	0,015		beta_w	0,015	
beta_D	0,015		beta_D	0,015	
K_s	0,1		K_s	0,1	
F	0,102		F	0,072	
C_eH	1,16		C_eH	1,02	
delta	0,02611	m	delta	0,00607	
Cg	2,0819188		Cg	2,08422379	