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# Timber-concrete hybrid structural systems
## – Examples, long and short-term dynamic evaluations, and numerical analysis

*Carl Larsson*

LINNAEUS UNIVERSITY PRESS

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Licentiate Thesis

Carl Larsson

**TIMBER-CONCRETE HYBRID STRUCTURAL SYSTEMS: EXAMPLES, LONG AND SHORT-TERM DYNAMIC EVALUATIONS, AND NUMERICAL ANALYSIS** Licentiate Thesis, Department of Building Technology, Linnaeus University, Växjö, 2023

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## Abstract

Timber-concrete hybrid buildings are an innovative solution to increase the amount of timber materials in modern buildings. Due to its lower impact on the environment than materials like steel and concrete, the demand for timber products is rising as the construction industry aims to decrease its environmental footprint.

Timber is naturally grown, and certain characteristics must be considered when used in buildings, such as strength and stiffness properties depending on variables like fiber direction and moisture content. In addition, timber is a lightweight material, which influences dynamic performance of timber elements and structures. To fulfill the requirements of a modern building, timber elements are sometimes combined with concrete elements, introducing timber-concrete hybrid buildings. This study aims to expand the use of timber-concrete hybrid buildings within the construction industry. The objective is to present different types of timber-concrete hybrid buildings and evaluate their structural performance to improve the level of knowledge for structural designers for the safe and robust design of such buildings.

Typically, four different types of timber-concrete hybrid structures are found in building projects in Sweden. These types of building projects usually involve additional designers than regular projects due to a lack of knowledge in timber design. Additionally, different designers uses different statical models for their designs, even within the same building project.

A mobile measurement system was developed to perform in-situ dynamic measurements. The system was used in a nine-story timber-concrete hybrid building during construction to investigate the dynamic properties and validate structural design models. A parameter study highlights different design parameters that have a large influence on these models. These parameters include the in-plane shear stiffness of CLT wall elements, the foundation properties, as well as non-load-bearing internal walls.

In addition, the long-term dynamic response of a four-story office timber-concrete hybrid building is presented. Over a three-years evaluation period, the results show a clear seasonal variation of the natural frequencies which correlates well with the moisture content within a CLT slab element. The results show that environmental effects are to be considered when comparing with finite element models. A predictive model is presented that can be implemented in a structural health monitoring system for damage detection so that these environmental effects can be filtered out.



**Keywords:** Timber-Concrete Hybrid Structures, Timber Design, Structural Dynamics, Structural Health Monitoring

# Sammanfattning

Hybridkonstruktioner i trä och betong är en innovativ lösning för att öka andelen trämaterial som används i dagens byggnader. På grund av träets fördelaktiga klimategenskaper i jämförelse mot traditionella byggmaterial som t.ex. stål och betong, har både utbudet av träprodukter och efterfrågan på dessa ökat.

Då trä är en naturlig råvara, finns det vissa egenskaper som måste beaktas när det används för byggproduktion. Som exempel påverkas styvhet och hållfasthet av variabler som fiberriktning och fuktkvot. Dessutom är trä ett material med förhållandevis låg densitet, som påverkar den dynamiska prestandan i byggnader som använder bärande träelement. För att möta de krav som ställs på dagens byggnader, kombineras i flera fall bärande element i trä med bärande element i betong. Denna typ av byggnad kallas hybridkonstruktioner i trä och betong. Arbetet syftar på att öka andelen hybridkonstruktioner inom byggsektorn. Målet med denna studie är att utvärdera hur den här typen av byggnader beter sig för att kunna ge konstruktörer ökad kunskap om säker och robust dimensionering.

Det här arbetet presenterar fyra olika typer av hybridkonstruktioner i trä och betong som används i Sverige. I den här typen av projekt används fler konstruktörer än i traditionella byggnadsprojekt, detta då kompetensen inom träkonstruktion är bristfällig hos de traditionella konstruktörerna. Dessutom använder konstruktörer olika antaganden och statiska modeller för sina beräkningar, även om de gäller samma byggnad.

Ett mobilt mätsystem har utvecklats för att kunna genomföra dynamiska mätningar på plats. Under byggtiden av ett 9-vånings flerbostadshus har det mobila mätsystemet använts för att fånga in dess dynamiska egenskaper och för att validera beräkningsmodeller. En jämförande studie visade vilka parametrar som i hög grad påverkar resultaten i dessa modeller. De avgörande parametrarna var främst skjuvstyvheten i KL-träväggarna, grundläggningen, samt icke-bärande innerväggar.

Långtidsmätningar av de dynamiska egenskaperna hos en 4-vånings kontorsbyggnad presenteras. Dessa resultat visar på en tydlig säsongsvariation i egenfrekvenserna hos byggnaden som korrelerar väl med den uppmätta fuktkvoten inuti ett KL-träbjälklag över mätperioden på tre år. Resultaten visar tydligt på att det omgivande klimatet bör beaktas vid jämförandestudier med en finita elementmodell. Utöver detta presenteras en modell som predikterar egenskaperna för implementering i ett system för tillståndsövervakning för skadedetektering så att den naturliga variationen kan filtreras bort.


**Nyckelord:** Hybridkonstruktion i trä och betong, Träkonstruktion, Strukturdynamik, Tillståndsövervakning

# Preface

The work presented in the thesis has been carried out at the Department of Building Technology at Linnaeus University under the supervision of Dr. Michael Dorn. The financial support is provided through Skanska Sverige AB, which has been my employer since I graduated in 2013. In addition to the funding acquired through my employer, financial support was provided by the Swedish Construction Industry's Organization for Research and Development (SBUF, project number 13721) and by the Knowledge Foundation (KKS, project number 20190026).

The project started as an idea when I worked as a structural designer for the *Växjö Train Station and City Hall* building. The load-bearing structure of the building was complicated, including structural elements in timber, cast-in-situ concrete, precast concrete, and steel. The timber parts included slabs in cross-laminated timber, a post-beam system in glulam timber, laminated veneer lumber of beech wood, and glulam timber trusses. As many unknowns were explicitly solved for this project, I thought there must be research-related topics within the field of timber-concrete hybrid buildings.

The path to performing dynamic testing and evaluation has not been a straightforward task for this work. First of all, I would like to thank my supervisor Michael Dorn (LNU) for believing in this idea, and for all help, comments, and guidance through this project. A special thanks to Osama Abdeljaber (LNU), who has inspired and helped me through this work, especially as the initial project plan did not include any dynamic measurements. An ambitious and long-shot idea to develop a mobile data acquisition system for dynamic measurements was established during the first year. It was successfully performed and completed thanks to Osama Abdeljaber (LNU), Michael Dorn (LNU), and Per Finander (Saab). The successful monitoring of House Biologen is thanks to the property developer Anders Persson (Granitor) and the contractor Andreas Jakopson (Värends Entreprenad). The evaluation of the long-term monitoring of House Charlie is thanks to Åsa Bolmsvik (Skanska, previously LNU), who initially installed the measurement system with financial support from Växjö Kommun and Videum AB. In addition, thanks to Thomas Bader (LNU), the SBUF reference group, and the KKS reference group for making this research possible.

Last and most important, I want to thank my family, especially my wife Emilie and my children Liv and Ebbot. This would not be possible without your love, patience, and support!

Växjö, Sweden, March, 2023
*Carl Larsson*

# Contents

# Publications

## List of appended papers

**Paper A**
Carl Larsson and Michael Dorn. A survey of the design of timber-concrete hybrid buildings in Sweden. *Planned for 2023 World Conference on Timber Engineering (WCTE), June 19 – 22, 2023, Oslo, Norway*.

**Paper B**
Carl Larsson, Osama Abdeljaber, Åsa Bolmsvik and Michael Dorn. Long-term analysis of the environmental effects on the global dynamic properties of a hybrid timber-concrete building. *Engineering Structures*, 2022, Volume 268. https://doi.org/10.1016/j.engstruct.2022.114726

**Paper C**
Carl Larsson, Osama Abdeljaber, Thomas Bader and Michael Dorn. Modal analysis and finite element model updating of a timber-concrete hybrid building. *In 6th International Conference on Structural Health Assessment of Timber Structures (SHATIS), September 7 – 9, 2022, Prague, Czech Republic*.

**Paper D**
Carl Larsson, Osama Abdeljaber and Michael Dorn. Dynamic evaluation of a nine-story timber-concrete hybrid building during construction. *Submitted to Engineering Structures, 2023, under review*. https://doi.org/10.21203/rs.3.rs-2505983/v1

## Other publications

**Paper E**
Carl Larsson. Växjö train station and city hall, a timber-concrete hybrid. *In 26th International Wood Construction Conference, Innsbruck, Austria, November 30 – December 2, 2022*.

**Paper F**
Michael Dorn, Carl Larsson and Osama Abdeljaber. Coupling of Weather Data to Moisture content in a Timber Building. *In 6th International Conference on Structural Health Assessment of Timber Structures (SHATIS), September 7 – 9, 2022, Prague, Czech Republic*.

## Authors contributions

**Paper A**

Larsson: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Visualization, Funding acquisition.

Dorn: Conceptualization, Supervision, Writing – review  editing, Funding acquisition.

**Paper B**

Larsson: Conceptualization, Investigation, Writing – original draft

Abdeljaber: Software, Data curation, Writing – review  editing.

Bolmsvik: Supervision

Dorn: Supervision, Writing – review  editing.

**Paper C**

Larsson: Conceptualization, Formal analysis, Investigation, Writing – original draft

Abdeljaber: Software, Data curation, Writing – review  editing.

Bader: Supervision

Dorn: Supervision, Writing – review  editing.

**Paper D**

Larsson: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization, Funding acquisition.

Abdeljaber: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – review  editing.

Dorn: Conceptualization, Supervision, Writing – review  editing, Funding acquisition.

# 1 Introduction

The manufacturing of building materials and the construction process of buildings and infrastructure are responsible for releasing about 10 % of the global carbon dioxide caused by human activity (United Nations, 2021). The buildings sector is a significant contributor to climate change, and there is a growing interest within the construction industry to reduce these emissions. In Sweden, there have been several agreements and initiatives within the industry in recent years to address this issue and promote more sustainable building materials and construction practices (Fossilfritt Sverige, 2018).

The load-bearing structure of buildings plays a significant role in their environmental impact (Malmqvist et al., 2018). In order to reduce this impact, it is necessary to consider alternative materials to traditional options such as steel and concrete. One such alternative is the use of timber, which has been shown to be effective in reducing the environmental impact of buildings (Younis and Dodoo, 2022). In fact, the use of timber has become increasingly popular in recent years due to its sustainability and renewable nature.

The replacement is though not without challenges. It is well known that buildings using timber in the load-bearing structure have difficulties fulfilling several requirements, e.g., due to the lack of self-weight of the material. In the ultimate limit state, uplift and overturning are some examples (Stoner and Pang, 2020). In the serviceability limit state, vibration requirements due to wind-induced loads are hard to fulfill (Landel, 2022). A solution to fulfill the requirements of a modern building project is introducing timber-concrete hybrid buildings where a combination of timber and concrete elements is used for the load-bearing structure.

## 1.1 The use of timber materials in modern construction

There is a great tradition of using timber as a structural material for buildings, especially in regions with large forest areas, such as Europe, North America, and Asia. There are several examples of old traditionally built timber buildings still standing. One of the oldest is the monumental building, the Horyuji Temple, Nara, Japan, built in the year 607 with a building height of 32 m. In addition, several timber buildings with a notable age, such as Kyrkboden, Ingatorp, Sweden, and Stålekleivloftet, Vindlaus, Norway, were built around the years 1200-1300.

In the last century, large timber buildings, such as multi-story buildings, were heavily regulated due to the potential danger of great city fires. In addition, there was a rapid development of other building materials, such as steel and concrete, during the early 1900s. This has resulted in the low use of timber in the construction industry for large-scale buildings.

Old timber buildings still standing are often known for their high level of craftsmanship, as each timber log was carefully selected and shaped using tools such as saws and axes. The timber industry has significantly developed in recent decades, resulting in a wide range of highly industrialized processed timber products. These products, including sawn timber, glulam timber (GLT), and laminated veneer lumber (LVL), are commonly used as beam elements in construction. Plate elements, such as plywood, cross-laminated timber (CLT), and oriented strand board (OSB), are also widely used.

The high level of prefabrication and the low weight of these products make them easy to transport and quick to install on-site. Therefore, timber construction systems have become competitive with other systems on the market. In addition, the advancement of knowledge in fire safety has allowed for the repeal of regulations limiting the size of timber buildings. Previous limitations, e.g., on the number of stories, have been replaced by performance criteria, which are valid independent of the type of building material. The combination of these factors has enabled the construction industry to utilize timber more extensively than previously possible.

### 1.1.1 Tree, wood, and timber

The material obtained from trees is used in several applications. When used as a structural material, the material from trees is defined as wood, a homogenous orthotropic material with three principal material directions, as shown in Figure 1.1. The longitudinal (L), radial (R), and tangential (T) directions are derived from the cross-section of a tree log where the growth rings are visible. The sawn material in Figures 1.1c abd 1.1d is called timber. The material properties in these directions significantly differ due to the cellular structure of wood on a microscopic scale.

As wood is processed for construction usage, the material is referred to as timber. Timber is a product derived from sawn tree stems and is commonly used as a building material. The cellular structure of wood determines the strength and mechanical properties of timber, and these properties are characterized and sorted into different classes. In addition, the moisture content (MC) of timber is of great importance, as it significantly affects the strength and mechanical properties of the material. Dry-out and wetting influence additionally dimensional stability and crack formation. In addition, a high MC favors the formation of fungi that break down the timber. Therefore, it is necessary to measure the MC accurately in order

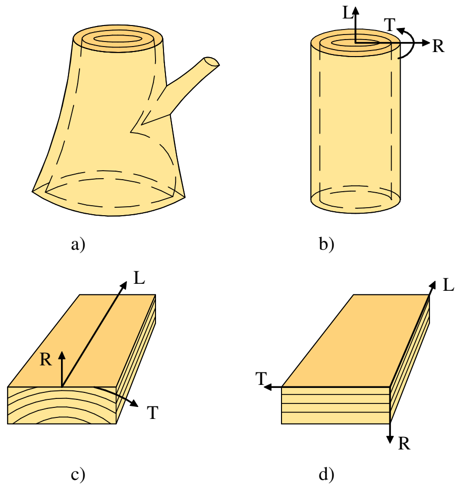



*Figure 1.1: From a tree stem to timber and a timber plank model. a) shows a timber stem with natural growth characteristics, b) a cylindrical tree stem model and principal directions, c) sawn timber with its cylindrical principal directions, and d) an orthotropic model of timber planks. It is based upon (Bodig and Jayne, 1982).*

to determine the correct properties of the material. The surrounding environment can influence the MC of timber, so it is essential to consider this when classifying the material to ensure that the properties are determined accurately.

Moisture in wood can exist in two forms: free water, the water within the lumen in the wood cells, and bound water, the water within the cell walls. MC of timber is defined as the ratio between the mass of the water and the mass of the dried timber, usually expressed as a percentage. The moisture content during construction should be in the range of the future use scenario to avoid negative consequences. Wood is therefore dried before further processing. All the free water is lost during the drying process before the bound water is reduced. This process is typically performed at sawmills, resulting in timber that contains only bound water within the wood cells.

The strength properties of timber typically have a negative correlation with the MC. However, a positive correlation is seen between density and MC. A standardized method for determining reference properties from test data is given in EN384 (European committee for standardization, 2016). By using this standard, it is possible to accurately determine the properties of timber and ensure that it is suitable for use in construction:

$$f_{(c,0)} = f_{(c,0)}(u)\Big(1 + 0.03(u - u_{ref})\Big) \tag{1.1}$$

$$E_0 = E_0(u)\Big(1 + 0.01(u - u_{ref})\Big) \tag{1.2}$$

$$\rho = \rho(u)\Big(1 - 0.005(u - u_{ref})\Big) \tag{1.3}$$

where $f_(c,0)$ is the compression strength parallel to the grain and $E_0$ the modulus of elasticity parallel to the grain. $\rho$ is the density, $u$ the MC for testing and $u_{ref}$ the reference value of 12 % MC for the tabulated values $f_(c,0)$, $E_0$ and $\rho$.

### 1.1.2 Cross-laminated Timber

One of the recent innovations in the timber industry is Cross Laminated Timber (CLT). It is an engineered wood product consisting of an uneven number of timber board layers, typically three to seven, as shown in Figure 1.2. The boards are arranged parallel to each other in each layer, and in adjacent layers they are arranged in a perpendicular pattern. The massive timber element shows good dimensional stability and is highly resistant to bending and other types of deformation within the surface dimensions. CLT elements are preferably used as slab and wall elements.

The construction method allows for the creation of a massive timber plate element that can be used in a variety of construction projects where precast concrete elements have previously been used. The use of CLT has increased rapidly in recent years due to its many advantages, including its strength, sustainability, and cost-effectiveness.

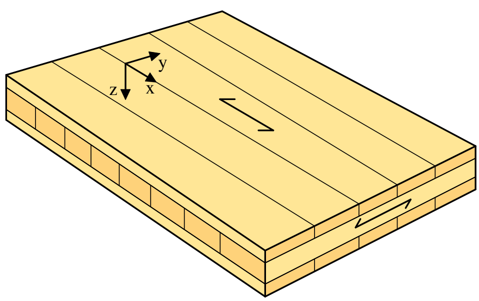



*Figure 1.2: A 3d view of a 3-layer CLT element with principal directions of the element.*

The technique of glued layers of timber material was previously developed for plywood and LVL in the early 1900s. In the 1990s, this technique was applied to timber boards introducing CLT. This was first done in Austria (Schickhofer, 1994) and Germany, and CLT was also known as massive timber, X-lam, or BSP (originating from the German word *Brettsperholz*). Two glue techniques are used in CLT production: non-edge-glued lamellas and edge-glued lamellas, both are available from different producers. In addition, there is a type of CLT that uses mechanical fasteners instead of glue, also called Nail Laminated Timber (NLT). However, this type is not that common (Muszyński et al., 2020).

With the introduction of CLT, several research projects started, especially at the Graz University of Technology. Later, research continued to develop, especially in Germany and Switzerland. Around the year 2000, the large-scale production of CLT began. In 2020, several CLT plants were in use worldwide, especially in Europe and North America, generating a good supply of CLT products for the construction industry (Muszynski et al., 2017).

One of the primary benefits of CLT is its suitability as a structural plate, allowing it to replace wall and slab elements in concrete. This makes it an attractive option for the construction industry, as it reduces the carbon footprint of buildings by replacing concrete elements with timber, which has a significantly lower carbon footprint. In addition to its environmental benefits, CLT has several other advantages over concrete, such as its lower weight, which makes it easier to transport, lift, and handle during construction. It can also be produced in a wide range of sizes, with widths up to 5 m, lengths up to 25 m, and thicknesses up to 400 mm, providing plenty of flexibility for use in modern timber buildings.

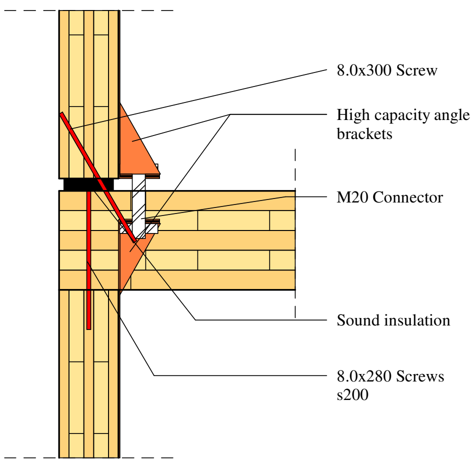



*Figure 1.3: Example of a wall-floor connector. The screws and angle brackets are to transfer load between elements. The M20 connector is used to fulfill requirements to prevent a progressive collapse of the building. Sound insulations are placed beneath each wall to reduce noise and vibrations between the wall and the slab.*

Despite its many benefits, the use of CLT is still relatively new, and design provisions and standardizations have yet to be fully developed. Austria was the first country to develop national guidelines in 2002 (Austrian Standards Institute, 2014), and the European standard (EN 16351) (European committee for standardization, 2021) was first approved in 2015. However, these guidelines are limited, and design provisions and product characteristics are still missing from the primary European standard for timber structures (EN 1995-1-1) (European committee for standardization, 2011). In the absence of comprehensive standardization, several handbooks have been developed to guide the design of CLT elements for structural use, including the *Cross-Laminated Timber Structural Design handbook* for the Central European market (Wallner-Novak et al., 2014), the *CLT Handbook* for the Canadian market (Karacabeyli and Brad, 2013), and the *KL-trähandboken* for the Swedish market (Gustafsson et al., 2019). In addition, CLT producers certify their CLT products to technical approvals, such as the European Technical Approval (ETA).

On a construction site, CLT elements are usually mounted using fasteners such as nails and screws arranged in different layouts and angles. For high-capacity joints, different type of steel plates are used to enable an increased number of fasteners in the joint. An example of such a joint can be seen in Figure 1.3.

## 1.2 The use of concrete materials in modern construction

Concrete has been used as a building material for thousands of years, as evidenced by the Göbekli Temple in Turkey, which is over 12,000 years old. The Roman Empire also extensively utilized concrete in their buildings, many still standing after 2,000 years. These examples highlight the durability of concrete as a building material.

Concrete has high compressive strength but is unsuitable for structural elements subjected to tension. However, when reinforced with materials such as steel bars, it becomes an ideal structural material that also can handle bending loads. The resulting material, known as reinforced concrete (RC), is commonly used for structural members in buildings, including beams, columns, slabs, and walls. These elements can be either cast in situ on the building site or produced off-site as precast concrete elements. The use of reinforced concrete has allowed for the construction of taller and more durable buildings, making it an important material in modern construction.

The use of concrete in the modern construction industry can be traced back to the early 1800s when Portland cement was first produced. Portland cement is a key ingredient in modern concrete, and its introduction allowed for large-scale production. Subsequently, this led to the development of reinforced concrete (RC) in the mid-1800s. The first known application of RC was in the construction of a four-story building in Paris in 1843. Since then, there has been rapid development in the use of concrete in construction, with the first high-rise 16-story building erected in Ohio, USA, in 1903. Today, the world's tallest building is the Burj Khalifa in Dubai, made preliminarily from concrete with a height of 828 m. This demonstrates the durability and versatility of concrete as a building material, contributing to its widespread use in modern construction.

### 1.2.1 Precast concrete elements

Precast concrete elements were first introduced in the construction industry in the early 1900s. Since then, their popularity has increased significantly due to the ability to complete on-site work quickly and efficiently and to standardized production methods for structural elements and fasteners. In addition, several innovations have improved the capabilities of precast concrete elements, such as the introduction of prestressing rebars, which have allowed for the creation of slab and beam elements with significantly increased span widths (Elliott, 2013).

In modern buildings, precast concrete elements are widely used in various structural members, including foundations, slabs, beams, walls, and columns. The dimensions of these elements are typically limited by factors such as the size of the precast manufacturing facility, transportation capabilities, and the maximum lifting capacity at the construction site.

During installation on the construction site, precast concrete elements are joined together using additional rebars and in-situ concrete infill for element-to-element connections, as shown in Figure 1.4. Alternative methods for connecting precast elements include the use of steel plates that are cast into the elements and subsequently welded on-site.

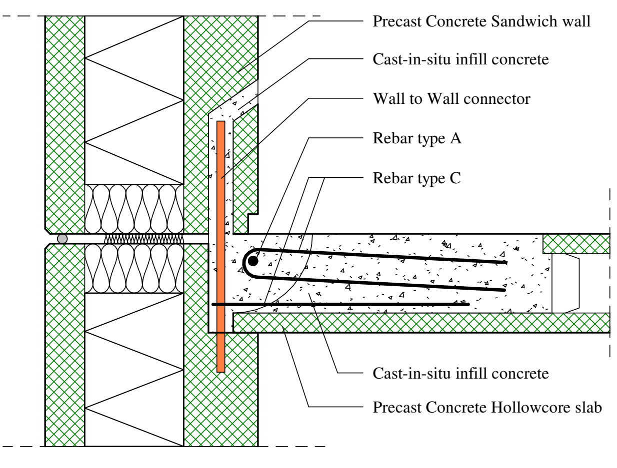



*Figure 1.4: Example of a wall-floor connector in a precast concrete building with sandwich walls and hollow core slabs. The wall-to-wall connector and rebars are used to transfer load and fulfill requirements to prevent a progressive collapse of the building.*

## 1.3 Timber-concrete hybrid buildings

The definition for timber-concrete hybrid buildings used in this thesis is a building in which the structural system above the foundation level includes structural elements made of both timber and concrete separately. This is shown in Figure 1.5. This type of structural system has gained popularity in recent years due to its numerous benefits, such as environmental footprint and lightweight elements, compared to traditional building methods. This thesis does not study structural elements consisting of both timber and concrete, known as timber-concrete composites. Such elements may, though be part of the load-bearing system.

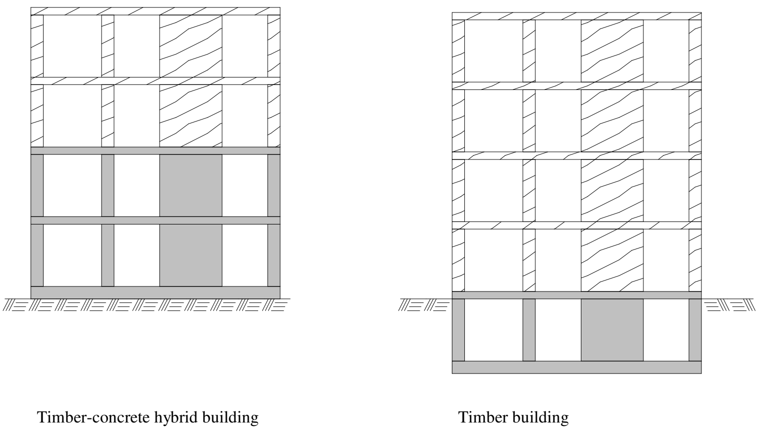



*Figure 1.5: The definition of a timber-concrete hybrid building and a timber building used in this thesis.*

As a part of this thesis, an interview study was conducted to categorize different types of timber-concrete hybrid structural systems. For the interview study, timber-concrete hybrid building projects in Sweden were selected that were recently finished or under production in early 2020. By conducting interviews with individuals involved in the planning and construction of these projects, valuable insight was gained into the reasons behind their adoption and any challenges encountered during the construction process.

The results of the study are presented in appended Paper A, which provides a comprehensive analysis of the investigated timber-concrete hybrid building projects. The paper includes a generalized description of the projects and an analysis of the reasons behind the use of the timber-concrete hybrid structural system and any structural challenges encountered.

### 1.3.1 Types of timber-concrete hybrid buildings

In Sweden, four different types of timber-concrete building system types are identified using this definition. These system types are shown in Figure 1.6.

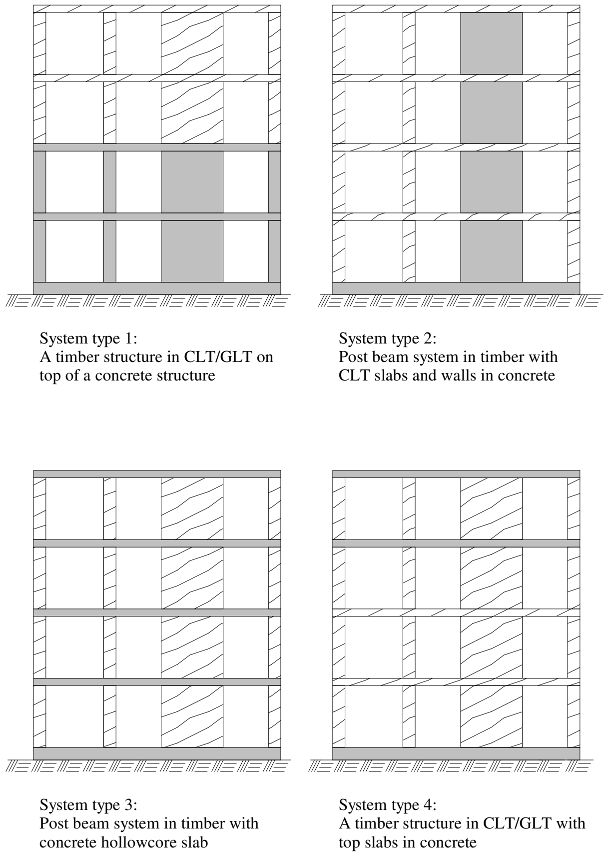



*Figure 1.6: System types of the load-bearing structure in a timber-concrete hybrid identified in appended Paper A.*

System type 1 consists of a timber structure on top of a concrete structure, the latter above the foundation level. This type of system is common in residential buildings for several reasons. Firstly, in residential buildings, the first floor often has a different plan layout than the rest of the building. Using concrete for the lower levels creates a homogenous, foundation-like slab so that the upper levels in timber can be easily mounted. Another reason is that the low weight of the timber elements often gives insufficient dead load to handle the uplift that the wind load gives. Concrete in the first floors adds sufficient counterweight, so this uplift is prohibited.

System type 2 is a typical solution for office buildings. A post-beam system creates an open-space floor layout in GLT and slabs in CLT. Concrete shear walls are used due to their higher capacity than CLT walls, often in combination with staircases or elevator shafts.

System type 3 is mainly used for schools or long-span office buildings where a typical CLT slab does not offer the span length required. The solution is to introduce prestressed concrete hollow core slabs supported by a post-beam system in timber. CLT walls, steel trusses, or timber trusses are used for lateral stability of the structure.

The last system, system type 4, is mainly used in high-rise buildings where additional mass is required for wind-induced vibrations. The extra mass is acquired by replacing timber slabs with concrete slabs on the top stories.

Timber-concrete hybrid buildings are proven to be efficient in high-rise timber buildings. The Council on Tall Buildings and Urban Habitat (2022) ranks the tallest buildings in the world. Of the 20 tallest mass timber buildings, twelve were timber-concrete hybrid buildings, and three were timber-concrete-steel hybrid buildings.

However, the definition of an all-timber high-rise building is a point of discussion, as several buildings marked as all-timber buildings on that list are timber-concrete hybrid buildings according to the definition in this thesis. For example, Mjøstårnet, Brumunddal, Norway, with a height of 81 m, used concrete slabs for additional self-weight in the top seven slabs (Abrahamsen, 2017), and Sara Kulturhus, Skellefteå, Sweden, has five stories with concrete slabs and a building height of 73 m (Skellefteå Kommun, 2021). Both buildings are categorized as System Type 4 according to the definition in this thesis. Regardless, these findings conclude that for mass-timber high-rise projects throughout the world, a majority of these are, in some way, timber-concrete hybrid buildings.

### 1.3.2 Collaborative design

As in other construction projects, there is a complex relationship between involved designers in the design process of timber-concrete hybrid structures. This is complicated by the fact that those combined systems are rather new, and design principles are not as widespread as for concrete or steel (Gosselin et al., 2018). According to the responses in Paper A, this complexity is also seen in the industry. For example, it was found that structural designers, in general, do not design timber elements as they do with steel and concrete elements, introducing an additional timber element designer in every project.

Efficient collaboration is essential for the successful design and construction of timber structures. The importance of data sharing was emphasized as a key factor in achieving this, according to the interviews. Computer-aided tools can facilitate collaboration, but these tools are often focused on building information modeling (BIM) and do not necessarily address the specific needs of structural design. The results of the study presented in the appended Paper A show that three types of software groups were commonly used for element design within projects; finite element software, frame analysis software, and specific software for just a single structural member type. These results show the important role of the individual designer as none of this software has any built-in functions for design collaboration and that a complete model of the load-bearing structure for design usage was seldom used.

In conclusion, the complex relationship between the structural designers in the design of timber structures highlights the need for improved collaboration and data sharing. As the use of timber in construction continues to grow, it will be important to develop new tools and strategies to support efficient collaboration between all the designers involved.

## 1.4 Structural health monitoring

Structural health monitoring (SHM) is a technique used to monitor the in-situ performance of buildings. It involves attaching various types of sensors to the structure to collect data on its performance, usually over long periods. This information is for instance used to determine whether the building operates within its design limits and to detect any potential structural damage.

The sensors used in SHM systems for buildings typically include dynamic sensors, which measure the dynamic performance of the structure, and hygro-thermal sensors, which monitor temperature and humidity levels both inside and outside the building, as well as within the building elements themselves. SHM systems typically require a large number of sensors, which means that a good infrastructure is needed for data acquisition, transmission, and management (Chen, 2018).

The hygro-thermal sensors are typically used to record environmental data to ensure that the building operates within its climate range of design. Meanwhile, dynamic sensors are usually used to determine the natural frequency of the structure, as any sudden changes in these frequencies may indicate structural damage (Catbas et al., 2008). If structural damage is detected, the SHM system can alert the property owner and recommend further building inspections. By real-time monitoring of a building's structural health, SHM systems can help property owners to identify and address potential issues in an early stage.

## 1.5 Research aims and tasks

This study aims to enhance the use of timber-concrete hybrid buildings within the construction industry. By giving examples, evaluating, and investigating the in-situ performance in timber-concrete hybrid buildings, the author wants to contribute with additional knowledge, especially since hybrid building systems with timber and concrete buildings are relatively new, both in the market and in research.

The objective is to present different types of common timber-concrete hybrid buildings and evaluate their structural performance. Several research projects, such as DynaTTB (Abrahamsen et al., 2020), have been conducted to learn more about the dynamics of mid-rise and tall timber buildings. For example, DynaTTB has performed the dynamic evaluation of the 84 m tall Mjøstårnet (Tulebekova et al., 2022) in Norway and the 22 m tall Yoker building (Kurent et al., 2021) in the UK. In addition, other studies in dynamic evaluations of timber buildings were performed in Norway (Aloisio et al., 2020), the US (Mugabo et al., 2019), and Italy (Reynolds et al., 2016). However, research solely focusing on timber-concrete hybrid buildings is less common.

Following the conclusions of the initial interview study in appended Paper A, several research tasks and questions were defined. In-situ assessments of realized timber-concrete hybrid buildings were considered necessary to understand their performance under real-life conditions. For such large structures, dynamic measurements are considered the most suitable. This led to the following tasks:

1. Find, categorize, and understand structural design challenges involved in timber-concrete hybrid buildings in Sweden.

2. Develop a dynamic measurement system suitable for ambient vibration testing and operational modal analysis that is easy-to-use in timber-concrete hybrid buildings, both during production and when finished.

3. Perform in-situ measurements to evaluate the dynamic performance of buildings with characteristics from the timber-concrete hybrid definition defined in task 1.

4. Perform finite element simulations of the tested buildings, including parametric studies, to investigate and evaluate parameters commonly assumed in a structural design process.

# 2 Methodology

The methodology used to fulfill the objective of this licentiate thesis includes several different tasks. As illustrated in Figure 2.1, these tasks include both short-term and long-term dynamic evaluations and numerical and analytical analysis. The figure also includes the appended papers and their relationship in between. The initial study in Paper A is considered an introduction and not covered in this chapter.

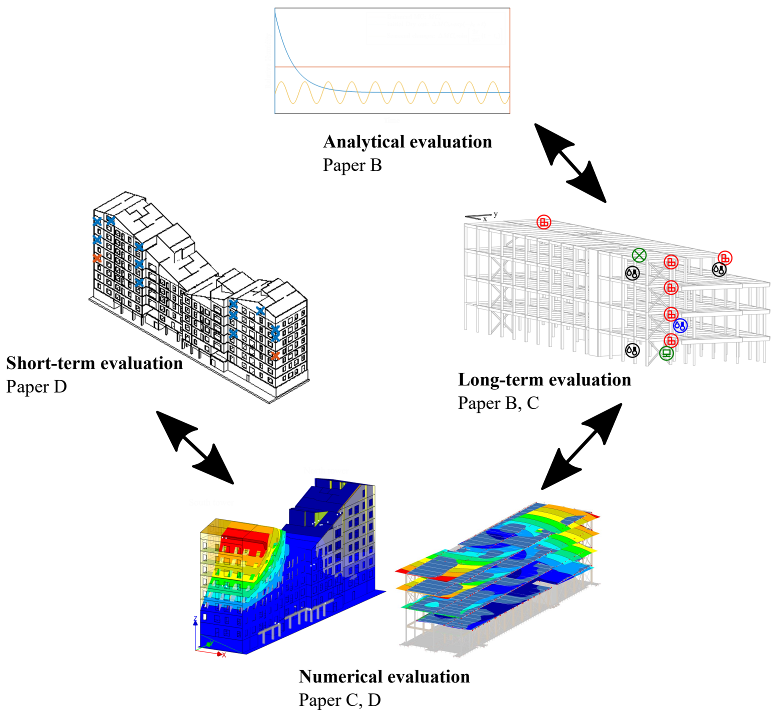



*Figure 2.1: The methodology used for the licentiate thesis, including the appended papers.*

## 2.1 Structural Dynamics

In papers B, C, and D, dynamic measurements are performed. The basics of structural dynamics are explained in the following section. The dynamic properties of a random structure can be described in a simplified way by studying the motion of a single degree of freedom (SDOF) system. A SDOF system is characterized by a mass ($m$), a viscous damper ($c$), and a spring ($k$), as illustrated in Figure 2.2. With a known impact force $F(t)$, affecting the system, the mass oscillates around its equilibrium position with a corresponding displacement $u(t)$.

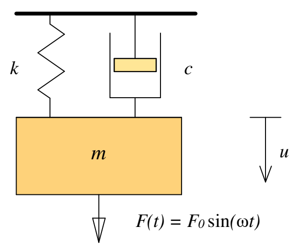



*Figure 2.2: A single-degree-of-freedom system illustrated.*

The equation of motion for the system given in Figure 2.2 can be described in the time domain by a second-order differential equation given in Equation 2.1.

$$m\ddot{u} + c\dot{u} + ku = F(t) \tag{2.1}$$

The natural frequency, given in Equation 2.2, describes at which frequency $\omega$ an undamped SDOF system freely vibrates.

$$\omega_n = \sqrt{k/m} \tag{2.2}$$

Damping is defined as how quickly such a vibration damp out. The damping ratio ($\zeta$) is calculated according to Equation 2.3. By including the damping in the formula for the natural frequency (Eq. 2.2), the damped natural frequency can be calculated according to Equation 2.4.

$$\zeta = \frac{c}{2\sqrt{mk}} \tag{2.3}$$

$$\omega_d = \omega_n\sqrt{1+\zeta^2} \tag{2.4}$$

## 2.2 Computational methods for modal analysis

Structural dynamic modal analysis on full-scale buildings is preferably performed using numerical methods. Finite Element Analysis (FEA) is a valuable tool since it is used to characterize the mass and stiffness of different structural system types. In a FEA, a global mass and stiffness matrix is built from the geometry and material properties of the included structural elements. With knowledge of the structural system's global mass (**M**) and stiffness (**K**) matrices, a modal analysis can be performed in the following steps to calculate the natural frequencies with corresponding mode shapes.

These methods are used in the appended papers C and D, where a FEA was performed for the buildings, and the results were analyzed.

### 2.2.1 Timber material model

The constitutive model used for timber is a linear-elastic orthotropic material model. In a FEA, the constitutive model can be described by Hooke's law in Equation 2.5:

$$\boldsymbol{\sigma} = \mathbf{D}\boldsymbol{\varepsilon} \tag{2.5}$$

where $\boldsymbol{\sigma}$ is the stress tensor, $\mathbf{D}$ is the material elasticity tensor in matrix notation and $\boldsymbol{\varepsilon}$ the elastic strain tensor. Equation 2.6 gives the constitutive equation expressed in matrix notation, using the principal material directions L-T-R given in Figure 1.1.

$$\underbrace{\begin{bmatrix} \sigma_L \\ \sigma_T \\ \sigma_R \\ \tau_{LT} \\ \tau_{LR} \\ \tau_{TR} \end{bmatrix}}_{\boldsymbol{\sigma}} = \underbrace{\begin{bmatrix} \frac{1}{E_L} & -\frac{v_{TL}}{E_T} & \frac{v_{RL}}{E_R} & 0 & 0 & 0 \\ -\frac{v_{LT}}{E_L} & -\frac{1}{E_T} & -\frac{v_{RT}}{E_R} & 0 & 0 & 0 \\ -\frac{v_{LR}}{E_L} & -\frac{v_{TR}}{E_T} & \frac{1}{E_R} & 0 & 0 & 0 \\ & & & \frac{1}{G_{LT}} & 0 & 0 \\ & sym. & & & \frac{1}{G_{LR}} & 0 \\ & & & & & \frac{1}{G_{TR}} \end{bmatrix}^{-1}}_{\mathbf{D}} \underbrace{\begin{bmatrix} \varepsilon_L \\ \varepsilon_T \\ \varepsilon_R \\ \gamma_{LT} \\ \gamma_{LR} \\ \gamma_{TR} \end{bmatrix}}_{\boldsymbol{\varepsilon}} \tag{2.6}$$

While the model above is used for solid elements in a FEA, CLT is usually modeled using shell elements. Hereby, the geometric and material properties of the different layers are combined into a single element.

According to the Mindlin-Reissner theory of shear-compliant shells (Mindlin, 1951), the general constitutive model for shells is shown in Equation 2.7. The factors $D_{11} - D_{33}$ describe the bending and torsional stiffness, factors $D_{44} - D_{55}$ describe the shear stiffness, and $D_{66} - D_{88}$ describe the membrane stiffness.

For CLT materials, there are several reduction factors introduced ($k_{33} - k_{55}$ and $k_{88}$) since the CLT plate cannot be seen as a completely homogeneous material. These factors reduce the shear and membrane stiffness values and depend on the type of CLT plate, the thickness of the individual layers, and the use of side-glued lamellas. Values for $D_{ij}$ and $k_{ij}$ in the stiffness matrix, given in Equation 2.7, are either provided by producers or can be taken from handbooks such as the Swedish CLT Handbook (Gustafsson et al., 2019).

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \\ V_x \\ V_y \\ N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & 0 & 0 & 0 & 0 & 0 & 0 \\ & D_{22} & 0 & 0 & 0 & 0 & 0 & 0 \\ & & k_{33}D_{33} & 0 & 0 & 0 & 0 & 0 \\ & & & k_{44}D_{44} & 0 & 0 & 0 & 0 \\ & & & & k_{55}D_{55} & 0 & 0 & 0 \\ & & sym. & & & D_{66} & D_{67} & 0 \\ & & & & & & D_{77} & 0 \\ & & & & & & & k_{88}D_{88} \end{bmatrix} \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \\ \gamma_x \\ \gamma_y \\ \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \tag{2.7}$$

### 2.2.2 Natural frequencies and mode shapes

For an undamped system, the equation of motion for a free vibration can be written according to Equation 2.8, where $\mathbf{M}$ is the mass matrix, $\mathbf{K}$ is the stiffness matrix, and $\boldsymbol{u}$ the displacement matrix.

$$\mathbf{M}\ddot{\boldsymbol{u}} + \mathbf{K}\boldsymbol{u} = \mathbf{0} \tag{2.8}$$

For a harmonic displacement, the solution is given by the assumption in Equation 2.9, where the eigenvalue $\omega_n$ and eigenvectors $\boldsymbol{\Phi_n}$ are introduced.

$$\boldsymbol{u}(t) = \boldsymbol{\Phi_n} e^{i\omega_n t} \tag{2.9}$$

The solution for the equation of motion for a free vibration is given in Equation 2.10. Equation 2.11 shows the corresponding equation for the eigenvalue $\omega_n$, that is the natural frequencies of the structural system. The solved eigenvectors $\Phi_n$ are dimensionless displacement vectors with determined relations between the different degrees-of-freedoms. These are defined as mode shapes and are collected in a modal matrix, given in Equation 2.12.

$$(\mathbf{K} - \omega_n^2\mathbf{M})\boldsymbol{\Phi_n} = \mathbf{0} \tag{2.10}$$

$$\omega_n^2 = \frac{\boldsymbol{\Phi_n^T K \Phi_n}}{\boldsymbol{\Phi_n^T M \Phi_n}} \tag{2.11}$$

$$\boldsymbol{\Phi} = \begin{bmatrix} \boldsymbol{\Phi_1} & \boldsymbol{\Phi_2} & \dots & \boldsymbol{\Phi_N} \end{bmatrix} \tag{2.12}$$

The mode shapes are usually visualized. For example, in Figure 2.3, the first three mode shapes of a cantilever beam are visualized.

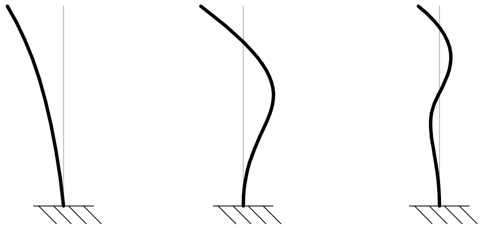



*Figure 2.3: Example of mode shapes for a cantilever beam where a) is the first mode, b) the second, and c) the third mode.*

## 2.3 Operational modal analysis

The operational modal analysis (OMA) method is widely used in the field of structural engineering for studying the modal properties of a structure under real-world operating conditions. The method involves the use of sensors, such as geophones and accelerometers, to collect data on the dynamic behavior of the structure, which is then combined with mathematical models to identify its natural frequencies and mode shapes (Brincker, 2015). The OMA method is used in Papers B, C, and D.

A main benefit of OMA is that the input load is unknown. It is thereby possible to do an in-situ ambient vibration test (AVT) of a structure without applying an additional known load. The OMA method consists of several steps in order to give an output for evaluating the dynamic response of a structure. These steps are visualized in Figure 2.4 and described in the following.

The first step is the gathering of acceleration data from the structure. Depending on the structure monitored, multiple acceleration recordings are required. In practice, one or several AVT points are assigned as reference points, left column in Figure 2.4, while the other points are progressively moved throughout the structure during the AVTs, right column. Each acceleration recording has to be performed for such a long time that some type of acceleration pattern is seen during further data analysis. As of this, the amount of time required differs depending on the structure the AVTs are taken from. The output from the AVT is a scatter of acceleration data, visualized in Figure 2.4a, where no obvious pattern is visible.

Statistical tools are used to analyze the data within the Time Domain. In this second step in OMA, auto-correlation and cross-correlation functions are used to find periodic patterns in the gathered acceleration data. The correlation methods are constructed to compare acceleration data in a specific time interval and compare it to the next time interval. Auto-correlation is used to compare data from the same location, while cross-correlation is used to compare data from different locations.

The output of this step is correlated values that now include periodic content, as visualized in Figure 2.4b.

The third step includes the translation from the time domain to the frequency domain. Since the correlated data now have a periodic content, Fourier Transformation is used.

The final step is to calculate the curve fit spectra. The dynamic properties can be calculated from this, including natural frequencies, mode shapes, and damping.

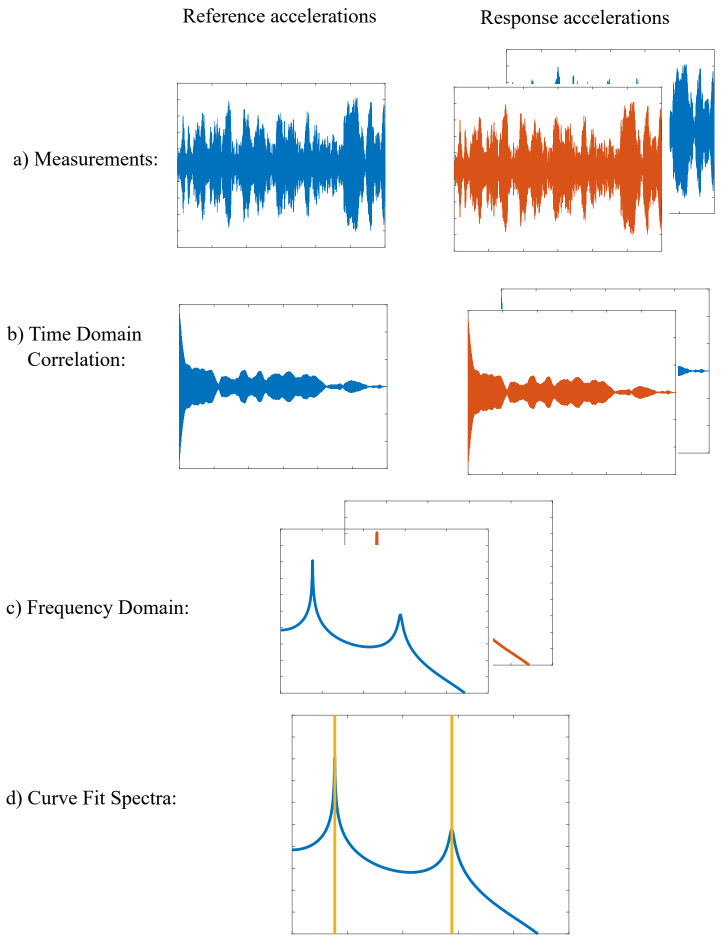



*Figure 2.4: OMA is explained in four steps: a) is the measured accelerations, b) time domain correlation using auto-correlation and cross-correlation functions, c) is the Fourier transform performed on the correlated data, and d) the curve fit spectra.*

The OMA is only valid for the assumption that the unknown load affecting the structure can be seen as white noise. White noise is characterized as spatially randomly distributed with an equal magnitude across the frequency range of interest. There are several cases where the white noise assumption is not valid, such as for rotating fans or running elevators, affecting the accelerations in the structure when the measurements are taken. These types of cases generate accelerations with a periodic pattern resulting in a load case that can't be described as white noise. OMA under this condition is invalid since the main assumption is not fulfilled.

### 2.3.1 Modal assurance criteria

The modal assurance criteria (MAC) is a commonly used statistical tool to compare mode shapes. The compared mode shapes can either be obtained numerically or measured experimentally. With two known mode shapes, for example $\mathbf{\Phi}_x$ from a FEA and $\mathbf{\Phi}_y$ from an OMA, the MAC can be calculated according to Equation 2.13.

$$MAC_{x,y} = \frac{(\mathbf{\Phi}_x^T \mathbf{\Phi}_y)^2}{(\mathbf{\Phi}_x^T \mathbf{\Phi}_x)(\mathbf{\Phi}_y^T \mathbf{\Phi}_y)} \tag{2.13}$$

A MAC value close to one shows that the mode shapes of the compared mode shapes are very similar. In contrast, a MAC value close to zero indicates that the compared mode shapes are entirely different.

## 2.4 Field measurements

In order to perform OMA, field measurements of accelerations of a structure are necessary. To collect this acceleration data, a data acquisition system is required that includes both sensors that collect the acceleration data and data acquisition devices that store this data with corresponding time stamps.

### 2.4.1 Objects

#### 2.4.1.1 House Charlie

House Charlie, in Figure 2.5, is a four-story office building in Växjö, Sweden. The four stories include 5,700 m$^2$, consisting mainly of office spaces, conference rooms, and supporting facilities. The building was constructed in 2017 and 2018 by the contractor JSB AB with Videum as the property developer. House Charlie opened in September 2018.

The building is 55 m in length, 14.5 m in width, and has a height of 16 m. The structural system consists of a post-beam system in GLT with CLT slabs. The building has two elevator shafts with shear walls in precast concrete and steel

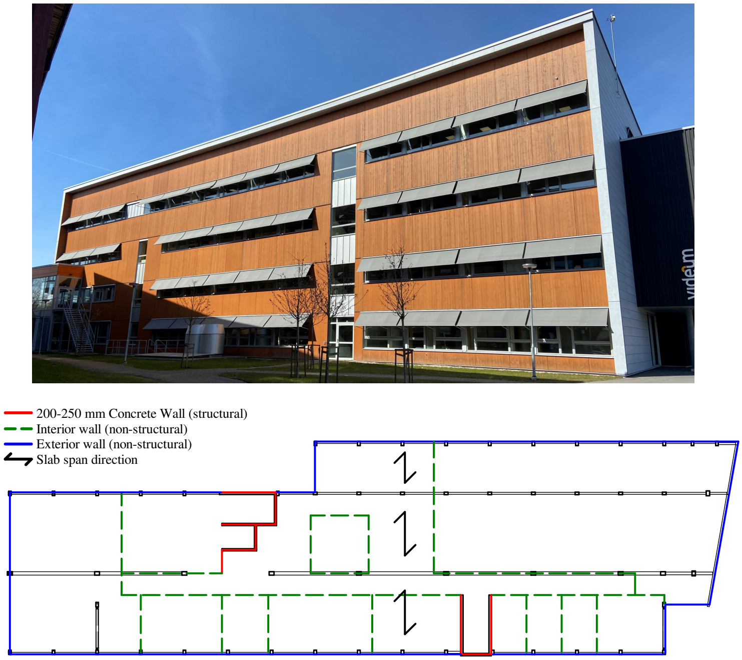



*Figure 2.5: Photo of House Charlie (top) and typical floor layout (bottom).*

bracings in two facades to provide lateral stability. This gives that the building is categorized as a System Type 2 building in this thesis. In addition to the structural system, there are non-structural walls in light-frame timber as well as a putty casting on top of the CLT slabs. The full plan layout is shown in the bottom of Figure 2.5.

#### 2.4.1.2 House Biologen 1

House Biologen 1, in Figure 2.6, is a nine-story residential building in Växjö, Sweden. The building includes four entries with a total of 70 apartments. The building is 68 m in length, 13.5 m in width, has a height of 28 m, and was built in 2021-2022. The building consists of a 3-7 story timber structure in CLT on top of a 2-story concrete structure and a concrete basement. The building is characterized by two higher sections, eight stories in the North and nine stories in the South. The building is categorized as a System type 1 building in this thesis and a typical timber floor plan is shown in the bottom of Figure 2.6.


*Figure 2.6: Photo of House Biologen 1 (top) and typical floor layout (bottom).*

### 2.4.2 Data acquisition

#### 2.4.2.1 Fixed installation at House Charlie

In paper B, the results and analysis from the long-term monitoring of House Charlie are presented. In the following, a short overview of the system is given.

The SHM system in House Charlie was installed during construction and has been running since the summer of 2018. Monitoring positions are distributed on all floors in the building. The attached sensors are combined temperature/humidity sensors, accelerometers and geophones, and displacement transducers, as well as a weather station on top of the building.

The fixed data acquisition system for House Charlie was developed and installed by the department of building technology at Linnaeus University in collaboration with SAAB. Details can be found in (Dorn et al., 2019). The author was not part of the development of this system, as it was installed in House Charlie before his Ph.D. studies. Since then, similar systems have been installed in two other buildings and used for laboratory-scale long-term measurements. However, these buildings do not include any dynamic measurements.

For that building, a total of 12 geophones were installed in pairs, collecting movement in two axes at six locations of the building. For each pair of geophone sets, one analog-to-digital converter (ADC) was connected. Each ADC card (Figure 2.7) has four inputs in total. Each input is equipped with a digital filter, a sample/hold amplifier, and a 24-bit A/D converter. In addition, a separate circuit board that amplified the geophone output by approximately 500 times was added. The ADC is powered by a power over ethernet (PoE) splitter.

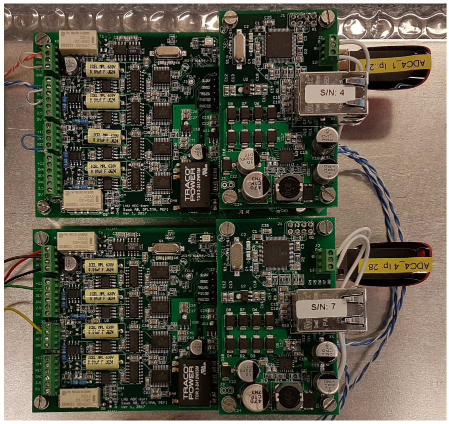


*Figure 2.7: Picture of two ADC card used for the measurements in House Charlie.*

Groups of sensors for relative humidity (RH) and temperature at different locations in the building were installed, most of them concerning the building envelope. Some sensors are drilled into a CLT slab, where the moisture content in the timber could be followed over time. Environmental readings were gathered using a weather station placed on the roof of the building, collecting outdoor temperature, humidity, wind speed, and wind direction. These temperature/humidity sensors and the weather station are connected to a separate sensor card.

A Raspberry Pi server is used to collect all data from the ADC cards as well as the sensor card regularly, and data is stored on site on an external hard drive. A wireless GSM router establishes remote control of the system.

There are several benefits to this system. The interval of the recordings could easily be changed during the monitoring period through the server. In addition, readings from one sensor could initiate the recording of measurement data for another sensor. For example, this was used for the wind speed sensor in the weather station. When the wind speed exceeded a specific value, the system was triggered to store and collect acceleration data from the geophones.

#### 2.4.2.2 Mobile data acquisition system

For short-term monitoring, a mobile data acquisition system, shown in Figure 2.8 was developed in order to conduct the AVTs for Paper D. The mobile data acquisition system was again developed in collaboration with SAAB.

The main objective was to overcome traditional systems' drawbacks: remove the need for cables between all attached sensors. Cabled systems cannot be used at a building site during ongoing production since this disturbs the daily work. But

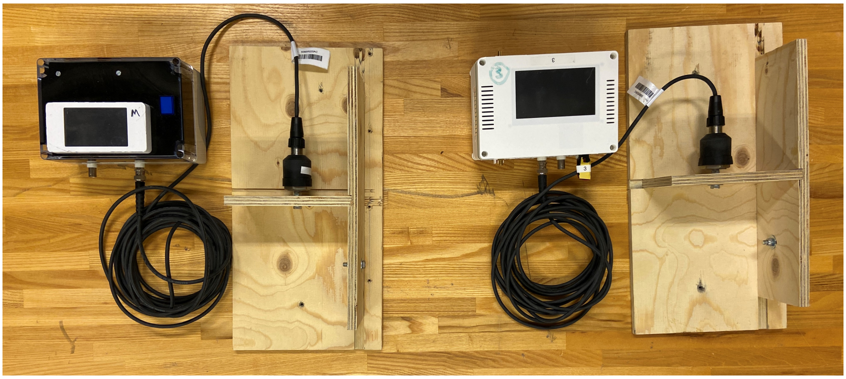


*Figure 2.8: A PCB393B12 accelerometer mounted on a plywood frame connected to the mobile data acquisition device during testing of the measurement system. The left shows one of two prototypes of mobile data acquisition devices. The right shows one of seven improved mobile data acquisition devices.*

also in finished buildings, the cables are, at least, annoying the users. On some occasions, they may not be installed at all, e.g., when led through different fire zones. Additionally, setting up the system is time intensive as it can easily lead to long cables.

In order to develop a mobile data acquisition system, several requirements are given so that an OMA is possible. The first requirement is that the system includes the necessary components to collect data from the accelerometers, similar to cabled systems. The second requirement is that mobile data acquisition devices have the capability to work synchronized with additional devices to collect the data fully synchronized in time, a challenge compared to cabled systems. In OMA, this is of great importance since the data is correlated within the time domain. The third requirement is that the system includes a display and user interface suitable for OMA. The final requirement is to make the system battery-driven and fully mobile without any electrical interference disturbing the signals from the accelerometers.

Initially, two prototypes were developed (Figure 2.8, left). The included components are shown in Figure 2.9. An extensive campaign of try-outs was performed, including laboratory tests where recordings from the prototype were compared to recordings from a $DataPhysicsDP700 - 60$ Dynamic Signal Analyzer device using the same test setup and accelerometers. In addition, full-scale testing of buildings with known natural frequency was studied. These buildings include House Charlie, where the fixed data acquisition system was installed, and Limnologen, where previous AVT had been performed (Reynolds et al., 2014). These systems were also used for the initial measurements in House Biologen 1, as presented in Paper D.

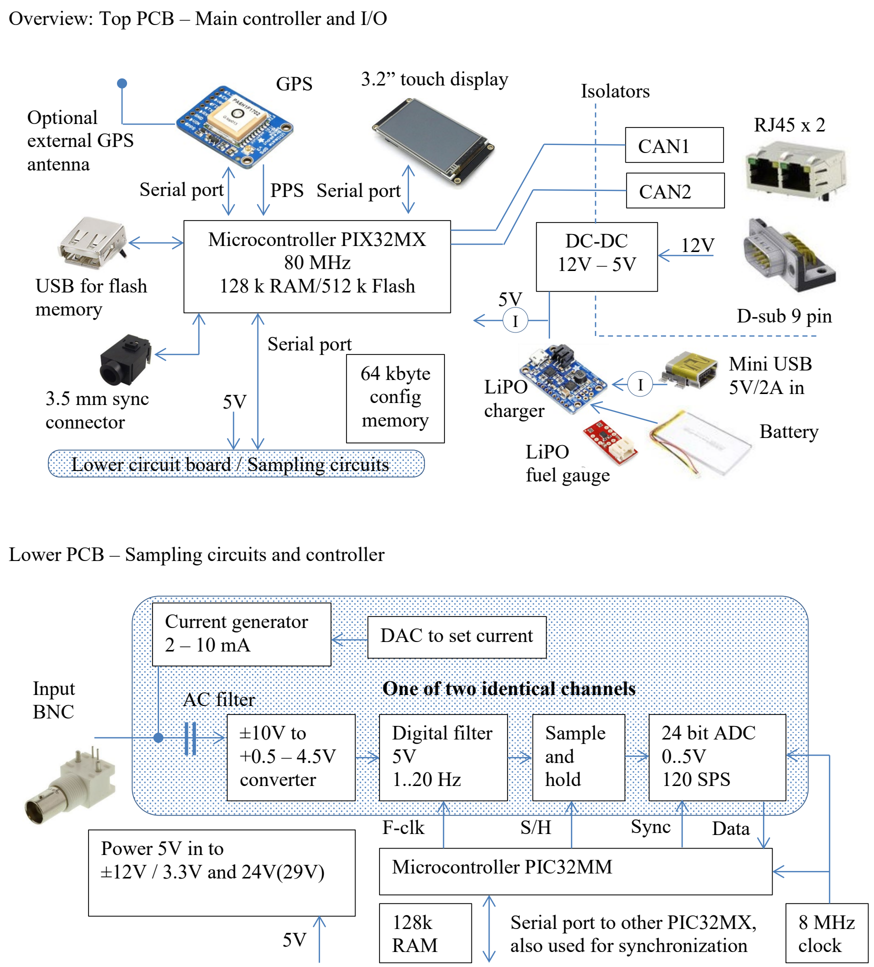


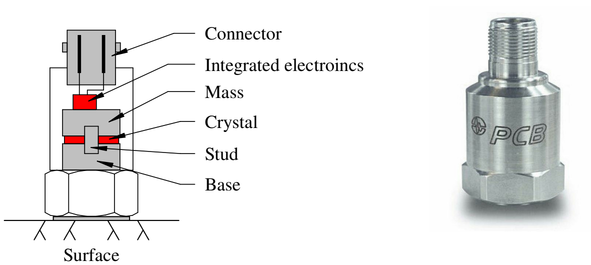

*Figure 2.9: Illustration of the included components and placement in the mobile data acquisition system developed by Linnaeus University and SAAB.*

An improved version was thereafter commissioned (Figure 2.8, right). While the basic features were identical, general bug-fixing was done, the systems create less noise, are easier to handle on site, and feature an improved interface for easier deployment. Additional features were included that allowed for a fixed installation as well, e.g., for use in laboratory environments. In total, seven improved units are available for up to 21 accelerometers to be connected. The improved systems were used for the later measurements in House Biologen 1, as presented in Paper D.

### 2.4.3 Sensors

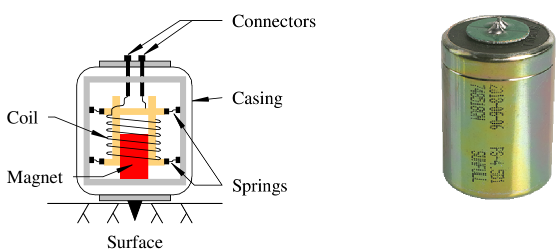
#### 2.4.3.1 Accelerometers

Accelerometers are the other type of sensor. In difference to geophones, the output signal from accelerometers is proportional to the acceleration. These sensors use piezo-electric crystals sandwiched between a mass and a fixed base material. Any movement of the sensor will cause the mass to move and deform the crystal, giving a proportional voltage output. See Figure 2.10 for a visualization of an accelerometer and the PCB393B12 from PCB used in this thesis.




a) b)

*Figure 2.10: a) Illustration of the components in an accelerometer, and b) the PCB393B12 used for the mobile data acquisition system.*




a) b)

*Figure 2.11: a) Illustration of the components in a geophone, and b) the Sunfull PS-4.5B used for the fixed data acquisition system.*

#### 2.4.3.2 Geophones

Geophones are passive sensors that record velocity and transform it into an electrical signal. The sensor consists of a mass attached to a spring, where the motion of the mass is measured using a magnet. Any movement of the mass induces a voltage signal proportional to the velocity. A geophone is only able to measure movement on one axis. This type of sensor is generally cheaper than accelerometers and is often used in seismic analysis of the earth. In general, geophones have a limited dynamic measurement range compared to accelerometers. Figure 2.11 shows an illustration of a geophone. The geophone used in this thesis is the PS-4.5B from Sunfull.

#### 2.4.3.3 Temperature and humidity sensors

The humidity sensors used in House Charlie are capacitive humidity sensors, SHT31, SHT35, and SHT75 from Sensirion. The RH is measured by placing a thin polymer between electrodes. The electrical capacity between the electrodes changes with the surrounding RH. The temperature is given by a silicon bandgap temperature sensor.

# 3 Summary of appended papers

## Paper A

Title: *A survey of the design of timber-concrete hybrid buildings in Sweden*

This paper is related to research task number one: *Find, categorize, and understand structural design challenges involved in timber-concrete hybrid buildings in Sweden.*

The objective of this paper is to gain information on the current situation for timber-concrete hybrid buildings in Sweden. The term timber-concrete hybrid building is defined. Ten different building projects in Sweden were identified and interviews with stakeholders, such as property developers, contractors, and structural designers, were performed.

The studied projects were grouped into four different types of timber-concrete hybrid structural systems that are also described in the introduction of this thesis. Developers motivated the increased use of timber with changing demands from within the construction sector, from municipalities and architects, as well as society in general. The favorable environmental footprint of timber was given as the main reason behind.

Several respondents highlighted uncertainties in collaborative design as a key issue. The practical works are divided between the different materials and the use of timber elements introduces one additional designer in each of the projects studied. These issues involve, amongst others, the information shared between the different designers and the use of separate calculation models for the same building.

Due to the concerns regarding collaborative design and the fact that these types of structural systems are new in the market, the further work presented here focuses on global structural analysis and in-situ evaluations of the building performance.

As an outcome of this initial study, potential industry-related research projects were identified for incorporation into the PhD studies.

## Paper B

Title: *Long-term analysis of the environmental effects on the global dynamic properties of a hybrid timber-concrete building*

This paper is related to research task number three: *Perform in-situ measurements to evaluate the dynamic performance of buildings with characteristics from the timber-concrete hybrid definition defined in the first task.*
The objective of this paper is to evaluate three years of continuous in-situ measurements of a timber-concrete hybrid building regarding the dynamic and hygrothermal performance.

A SHM system was installed in the four-story office building House Charlie, categorized as a system type 2 building according to appended Paper A. A previous research group consisting of Bolmsvik, Klaesson, Enquist, Brandt, and Finander performed the installation of the monitoring system in the building. The system includes dynamic measurements using geophones and hygro-thermal measurements using relative humidity and temperature sensors. A weather station was used to collect exterior temperature and humidity, wind speed and wind direction, and solar radiation affecting the building. The recordings started in July 2018 and were evaluated until September 2021, spanning a bit more than three years.

The Operational Modal analysis (OMA), performed on the geophone data, showed three clear mode shapes of the building with corresponding natural frequencies and damping. The natural frequencies showed a seasonal variation, where the highest natural frequencies were recorded during September/October, and the lowest were recorded in March/April. E.g., the first natural frequency differed between 3.04 Hz and 3.41 Hz during the period. The recorded damping showed no seasonal pattern and was recorded in the interval of 1.5 % to 3.5 % for the corresponding three mode shapes.

The analysis of relative humidity in a CLT slab located on the first floor of the building showed a similar seasonal pattern as for the natural frequencies. The readings showed that the relative humidity within the CLT plate was highest during September/October and lowest in March/April. The open underside of the plate showed higher variations than the upper side which was covered by concrete and flooring. Temperature, meanwhile, was rather constant due to the climatization during summer and heating during winter, also in the thickness direction.

The relative humidity and temperature readings were recalculated to a moisture content for the CLT plate that showed the same seasonal variation and geometric distribution. A correlation analysis between the moisture content (MC) in the CLT slab and the recorded natural frequencies for the entire building gave a clear trend, and correlations coefficients were as high as $R^2 = 0.81 - 0.84$. It is particularly interesting since the governing structural elements for lateral stability are built in other materials, such as concrete shear walls and steel bracings, which are not equally influenced by seasonal variation.

Finally, a model was developed to predict the moisture content within the CLT plate. The model proved accurate, with correlation values $R^2 = 0.948 - 0.999$. The following parameters were introduced for the model:

1. Dry-out: The material is assumed to dry out over time, as the timber arrives with a higher moisture content from production and is expected to dry out to a point where the timber material is in equilibrium with its surroundings.

2. Seasonal variation: As the relative humidity level in the surroundings varies over the year, a second variable is introduced describing these seasonal variations.

3. Long-term average: After the dry-out phase, it is assumed that the seasonal variation varies around the long-term average

The same model was applied to predict the natural frequencies of House Charlie due to the high correlation with the MC. The model gave a high correlation with $R^2 = 0.765 - 0.805$, even though the correlation is lower than the correlation of MC in the CLT slab. This predictive model is of great importance, especially in damage detection through SHM. As a change in the recorded natural frequencies indicates structural damage, it is of utmost importance to know whether the recorded change can be derived from natural changes or not. In addition, the variation in the natural frequencies and the influence of the MC on the strength properties of timber is further investigated in Paper C.

The seasonal changes in the eigenfrequencies are also of significance when assessing the dynamic performance of a building. A variation of more than 10 % has been observed in House Charlie, which is non-negligible. Since House Charlie is a low-rise building, swaying is not an issue. In high-rise buildings, the influence of naturally occurring seasonal changes could be important.

## Paper C

Title: *Modal analysis and finite element model updating of a timber-concrete hybrid building*

This paper is related to research task number four: *Perform finite element simulations of the tested buildings, including parametric studies, to investigate and evaluate parameters commonly assumed in a structural design process.*

The objective of this paper is to investigate the seasonal variation in the measured natural frequencies of House Charlie (Paper B) and if these can be modeled in a FEA. In addition, the influence of non-structural elements is studied.

The project initially started as a master's thesis by Svanberg and Petersson (2021) that Larsson supervised. The purpose of the thesis was to evaluate the mobile data acquisition system that the research group developed and to compare the results with results from the fixed system installed in House Charlie (Paper B). The master's thesis included a finite element model of the building. A model updating procedure was performed to acquire a model that can be compared with the results from the measurements using the mobile data acquisition system related to research task 4.

The appended paper differs, however, from the initial master's thesis. The paper used OMA performed on the acceleration data given by the fixed system used in Paper B. Finite element simulations were performed with varying timber characteristics that changes in MC can cause. In specific, the MC was investigated in the interval 8 % to 16 %, affecting density ($\rho$) and stiffness ($E_{ij}$,$G_{ij}$), and strength values ($f_{mk}$).

The analysis concludes that the recorded seasonal variations cannot be derived from the varying density and stiffness properties of the timber material in the FE model. The results from the FE analysis showed that for an increased MC, the natural frequency decreased. This is in line with the original expectation that an increase in moisture content (MC) would result in higher density and mass, as well as decreased stiffness properties, leading to a decrease in the natural frequencies. However, the results from House Charlie were contrary to this expectation. It was observed that changes in the eigenfrequencies followed changes in the moisture content. The eigenfrequencies were found to correspond with changes in moisture content, suggesting that additional factors influence the measured natural frequencies of the timber in House Charlie, beyond density and stiffness properties.

In addition, an analysis of the influence of non-structural elements in the FEA was performed. These elements were included as added both as masses and by their contribution of additional stiffness. It was shown that non-structural walls had a significant influence on the eigenfrequencies and are non-negligible.

## Paper D

Title: *Dynamic evaluation of a nine-story timber-concrete hybrid building during construction*

This paper is related to research task number two, three and four: *2) develop a dynamic measurement system suitable for ambient vibration testing and operational modal analysis that is easy-to-use in timber-concrete hybrid buildings, both during production and when finished; 3) perform in-situ measurements to evaluate the dynamic performance of buildings with characteristics from the timber-concrete hybrid definition defined in task 1 and; 4) perform finite element simulations of the tested buildings, including parametric studies, to investigate and evaluate parameters commonly assumed in a structural design process.*

The objective of this paper is to follow the dynamic performance of a timber-concrete hybrid building during construction. The study was performed on House Biologen 1, categorized as a system type 1 building according to Paper A. The nine-story building consists of two concrete stories and seven stories of CLT elements on top.

A custom-built mobile measurement system was developed for AVT, as commercial systems were not accessible to the research group. This system was utilized for a period of 13 months to conduct seven successful AVTs of House Biologen at various stages of construction. The advantage of using a mobile system was that it allowed for AVT to be performed without disrupting the ongoing construction work on the site, unlike traditional cabled systems.

The initial four AVTs conducted during construction identified only one natural frequency. However, the final three AVTs, performed when all structural elements were in place, revealed two clear mode shapes. The results show that the natural frequencies decreased as additional mass was added to the slab. Additionally, it was concluded that there was a stiffness increase in the building when the façade and non-structural walls were installed.

With the large number of AVTs available for calibration of a FE model, an investigation of the influence of different parameters on the dynamic characteristics was performed thereafter. The parameters chosen are typical of importance during the design phase for both static and dynamic structural analysis of a building project, e.g., material stiffness, connection compliance, or soil properties. To accomplish this, FE simulations were performed for each of the AVTs.

Through an initial FEA of the building with rough assumptions of model parameters, the eigenmodes and corresponding eigenfrequencies were found to match the experimental ones roughly. The following parameter variation study emphasized the significance of accurately modeling the cross-laminated timber (CLT) material, as in-plane shear stiffness significantly impacted the results. The foundation characteristics and non-structural wall elements were also identified to have a notable effect on the results of the FEA, which is in line with the conclusions made in Paper C for House Charlie.

Finally, a combination of properties that showed good agreement with the measured eigenfrequencies from the ambient vibration tests (AVTs) was presented. It is emphasized that numerous parameters influence the results in different ways. A "correct" set of parameters was intentionally not presented as such a set cannot be verified uniquely.

The appended paper concludes a successful use of the mobile dynamic measurement system that was developed within the scope of this thesis. The evaluation of the OMA showed that non-structural elements clearly increased the stiffness of the building. In addition, it concludes that using commercial software, a standard FE model for design successfully gives natural frequencies and mode shapes comparable to the measured values.

# 4 Discussion and Conclusions

The initial interview study resulted in some unexpected conclusions, as the thesis initially hypothesized that the main concern was the limited knowledge of the design of timber-concrete connections. The findings in Paper A showed concern by the involved designers in the number of structural designers involved, the fact that they used different statical approaches and different types of computational aid in performing their design calculations. According to Fröderberg and Thelandersson (2015), there is a large variation in design loads for single structural elements reported by practicing designers given a realistic load-takedown task. This implies that the increased number of designers involved in timber-concrete hybrids may result in even higher variation of design loads, causing uncertainty in the design loads for single structural elements. These findings combined concluded that conducting FE analysis on fully modeled timber-concrete hybrid buildings and comparing the results to in-situ measurements can be a way to verify the design.

Dynamic measurements are an adequate method for measuring full-scale structures. In the thesis, the method is applied on two studies on different timber-concrete hybrid buildings: the first study with a three-year, long-term analysis of a realized building in use; the second study for multiple short-term measurements during construction. In both cases, the results are compared to numerical models.

In Paper B, the seasonal variation in the recorded natural frequencies of House Charlie was expected, since the moisture content in timber is known to vary with its surroundings. In addition, several other studies regarding buildings in other materials conclude the environmental impact of recorded natural frequencies, both in modern buildings, such as Clinton et al. (2006), and adobe buildings, such as Zonno et al. (2019). The recorded natural frequencies of House Charlie suggest a seasonal variation of around 10 %. This variation is considerable when used for the validation of a FE model. For example, in a model update procedure, many of the variables used in a FE analysis affect the natural frequencies at a lower magnitude than this seasonal variation.

In Paper C, a model update procedure for House Charlie is presented. The results show that the recorded variation cannot be modeled easily. Originally, a negative correlation between moisture content and frequencies was expected, as a higher MC in the timber material gives the material a higher density and mass as well as lower strength and stiffness. This will cause a decrease in the natural frequencies, which the finite element analyses also showed. However, a positive correlation was observed in House Charlie: the natural frequencies rise when the MC within the timber material rises. In paper B, some possible explanations are given for factors beyond density and stiffness properties. In this work, the cause of these results are not further investigated and covered.

In Paper D, the construction of House Biologen 1 is followed by dynamic measurements to further evaluate the dynamic performance of timber-concrete hybrid buildings. The results show that non-structural elements wall affect the overall stiffness and natural frequencies of the building, although 94 % of the walls are structural walls in CLT. The findings are consistent with other studies (Devin and Fanning, 2019), that non-structural walls affect the dynamic response of buildings regardless of the structural material and that these elements should be included in a FE analysis.

In addition, the in-plane shear stiffness of the CLT walls was identified to have a large impact on the FEA results. For a good fit with the results from the AVTs, the in-plane shear stiffness had to be reduced significantly. One hypothesis is the use of acoustic insulation under each wall has a high impact, which may numerically be covered by a reduced shear stiffness. This has previously been shown by Azinović et al. (2021), that concluded that the elastic stiffness of an acoustic insulated wall is less than 40 % that of an uninsulated wall at low vertical loads and a more flexible acoustic insulation.

No formal model updating of the FE model of Biologen 1 was performed since the influence of environmental factors is unknown for the building. The AVTs were taken over 13 months, giving a timelapse that includes a dryer and a more humid season. However, a sensitivity analysis was performed using different design approaches to verify their influence on the model. The results showed that the inclusion of a soil-structure interaction model affects the natural frequencies, opposite the conclusion made for a similar CLT building using a piled foundation (Kurent et al., 2021). In contrast, element connectors, in terms of hinged and fixed connections, did not influence the natural frequencies much, similar to the conclusion by Aloisio et al. (2020).

Finally, the overall conclusion is that timber-concrete hybrid buildings fulfill the requirements for a modern building. This, of course, requires good knowledge of designing with timber and the material's specialties. By developing a dynamic measurement system and perform AVTs and corresponding OMA in Paper B and Paper D, data are gathered that can be used for comparison with FE models. Regarding collaborative design, the corresponding analysis in Paper C and Paper D contributes to the general knowledge of the behavior of timber-concrete hybrid buildings. By incorporating this information, designers involved in the design process can make more informed and precise decisions.

# 5 Future Work

The work presented in this thesis presents the first part of my doctoral studies, accomplished between October 2019 and March 2023. The project will continue and later be presented in a Doctoral thesis.

The following projects are planned for the doctoral thesis:

- Perform multiple AVTs on two five-story timber-concrete hybrid buildings with an identical timber structure but a concrete structure that differs. The aim is to investigate if there are any differences in the dynamic responses of the buildings and evaluate the influence of the concrete substructure in a finite element simulation.

- Perform multiple AVTs on a 54 m high-rise timber-concrete hybrid building under construction. The aim of the AVTs is to verify the dynamic properties of a tall building in a wind-prone region during construction. The design frequencies of the building are well below 1 Hz.

- Study how the dynamic properties of CLT elements are affected by their surrounding temperature and humidity in a controlled climate chamber. The aim is to investigate the findings in Paper D deeper.

Apart from my doctoral studies, the following topics are seen as relevant in this field:

- In terms of understanding the natural frequencies of timber-concrete hybrids, it is of great importance to conduct further long-term monitoring of the dynamic response in these types of buildings.

- The work does not explain the positive correlation between the MC and natural frequencies found in this thesis. A primary task for future research is to explain this. These findings will be necessary, both in terms of using OMA to validate FE models of buildings and for using SHM for damage detection in timber-concrete hybrids.

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