

Linnaeus University Dissertations
No 596/2025

CARL LARSSON

TIMBER-CONCRETE HYBRID BUILDINGS

Insights from Field Monitoring, Dynamic Behaviour, and Numerical Simulations



LINNAEUS UNIVERSITY PRESS

Timber-Concrete Hybrid Buildings

Insights from Field Monitoring, Dynamic
Behaviour, and Numerical Simulations

Linnaeus University Dissertations

No 596/2025

Timber-Concrete Hybrid Buildings

Insights from Field Monitoring, Dynamic Behaviour, and Numerical Simulations

Carl Larsson

LINNAEUS UNIVERSITY PRESS

**Timber-Concrete Hybrid Buildings: Insights from Field Monitoring,
Dynamic Behaviour, and Numerical Simulations**

Doctoral Dissertation, Department of Department of Building
Technology, Linnaeus University, Växjö, 2025

ISBN: 978-91-8082-376-0 (print), 978-91-8082-377-7 (pdf)

© Carl Larsson

DOI: <https://doi.org/10.15626/LUD.596.2025>

Published by: Linnaeus University Press, 351 95 Växjö

Printed by: Exakta Print AB, 2025

Abstract

Timber–concrete hybrid buildings present a promising approach to increasing timber use in modern construction, offering environmental benefits over traditional materials like steel and concrete. Yet, timber’s characteristics, being orthotropic, lightweight and of natural origin, pose challenges in structural design. A key factor in the design process is effective collaboration among multiple structural designers, who often work within their respective materials and use different model assumptions. This may lead to significant model uncertainties, which can jeopardise the reliability, safety and efficiency of timber–concrete hybrid structures.

To address this, a comprehensive measurement campaign was initiated in this thesis project alongside studies of design models. The goal was to identify influential parameters, clarify modelling assumptions, and enhance reliability in structural analysis. This thesis contributes to the understanding of timber–concrete hybrid systems by evaluating their structural behaviour through in-situ measurements, finite element modelling, and model updating.

This thesis is structured around four timber–concrete hybrid projects at varying stages of completion, including both realised and ongoing developments. The first building, a four-story office building, involved a three-year monitoring campaign, which demonstrated that seasonal variations in dynamic properties strongly correlated with moisture content in CLT slabs. A predictive model was developed to calculate these variations, enabling improved structural health monitoring. To further widen the study, a modular mobile measurement system was developed to perform Ambient Vibration Tests. It was deployed in three buildings during construction so that the construction steps could be followed separately: the dynamic behaviour of a nine-story building was tracked through seven construction stages, revealing the influence of non-structural elements and slab finishing on natural frequencies; two nearly identical six-story buildings with different substructures and soil conditions demonstrated that the timber superstructure dominates the dynamic response, with the in-plane shear stiffness of CLT walls being the most influential parameter; an 11-story building was monitored through seven construction stages, highlighting the evolving contribution of connections and non-structural elements to global stiffness.

The findings from this combined experimental-theoretical approach contribute to more robust design practices, improved predictive modelling, and the development of structural health monitoring systems tailored for timber–concrete hybrid structures.

Keywords: Timber–Concrete Hybrid Structures, Structural Dynamics, Ambient Vibration Testing, Structural Health Monitoring, Model Updating

Sammanfattning

Hybridkonstruktioner i trä och betong är en innovativ lösning för att öka andelen trämaterial i byggnader och därmed minska miljöpåverkan jämfört med om traditionella material som stål och betong använts. Trämaterialets unika ortotropiska egenskaper, låga vikt, och naturliga ursprung medför dock utmaningar vid dimensionering. Denna avhandling syftar till att öka förståelsen och tillämpningen av hybridkonstruktioner genom fältmätningar och finita elementmodeller för att utvärdera parametrar som används vid dimensionering.

En utmaning i projekteringsprocessen är att säkerställa effektiv samverkan mellan konstruktörer, som ofta är specialiserade på ett material och använder olika antaganden och beräkningsmodeller. Detta kan leda till modellrelaterade osäkerheter som påverkar resurseffektivitet, utnyttjandegrader och konstruktionens tillförlitlighet. Avhandlingen adresserar dessa problem genom en omfattande mätkampanj som kombineras med analyser av beräkningsmodeller. Målet är att identifiera parametrar med avgörande inverkan, tydliggöra modellantaganden och höja tillförlitligheten i strukturanalysen. Studien bidrar till en fördjupad förståelse vid projektering av hybridkonstruktioner genom dynamiska mätningar, finita element-modellering och uppdatering av modeller.

Studien baseras på fyra färdigställda eller pågående byggnadsprojekt. Det första, en fyrvånings kontorsbyggnad, omfattar en treårig mätperiod som visade stark korrelation mellan säsongsvariationer i dynamiska egenskaper och fukthalten i ett KL-träbjälklag. En prediktiv modell utvecklades för att kvantifiera dessa variationer, viktiga vid tillståndsovervakning.

För att utvidga undersökningarna utvecklades ett modulärt och mobilt mätsystem för Ambient Vibration Tests. Systemet användes i de tre övriga byggnaderna under ett produktionsskede som möjliggjorde en analys av byggprocessens inverkan på det dynamiska beteendet. I en nio våningsbyggnad följdes dynamiska egenskaper genom sju byggskedet, vilket tydliggjorde betydelsen av icke-bärande element och bjälklagsytbehandling för egenfrekvenserna. Två nästan identiska sexvåningsbyggnader med olika grundläggning visade att träöverbyggnaden dominerar den globala dynamiska prestandan, där KL-träväggarnas skjuvstyvhet i planet var mest inflytelserik. Slutligen gjordes fältmätningar för en elvåningsbyggnad under sju byggskedet, vilket belyste den successiva ökningen av global styvhet till följd av förband och icke-bärande element.

Resultaten från det experimentellt-numeriska tillvägagångssättet bidrar till utvecklingen av robustare dimensioneringsmetoder, förbättrade prediktiva modeller samt implementeringen av avancerade system för tillståndsovervakning, särskilt anpassade för hybridkonstruktioner i trä och betong.

Nyckelord: Hybridkonstruktion i trä och betong, Träkonstruktion, Strukturdynamik, Tillståndsovervakning

Acknowledgments

First and foremost, I would like to express my deepest gratitude to my family. To my wife, Emilie, and my children, Liv and Ebbot, your love, patience, and unwavering support have been the foundation of this journey. Thank you for standing by me through every challenge and for giving me the strength to keep moving forward.

I am also sincerely grateful to my friend and office mate, Dr. Osama Abdeljaber. We have shared many ideas, some good, some less so, and working alongside you has made this experience both enjoyable and productive.

I extend my heartfelt thanks to my main supervisor, Dr. Michael Dorn, for his openness to ideas and always saying yes, and for his continuous guidance, encouragement, and academic support throughout this project.

The work presented in this thesis has been carried out at the Department of Building Technology at Linnaeus University under the supervision of Dr. Michael Dorn. The financial support was provided by Skanska Sverige AB, the Swedish Construction Industry's Organisation for Research and Development (SBUF, project numbers 13721 and 14251), and the Knowledge Foundation (KKS, project numbers 20190026 and 20230005).

I am deeply thankful to the whole supervision team with Dr. Michael Dorn, Dr. Osama Abdeljaber, and Dr. Åsa Bolmsvik, for their trust in my ideas, and for their invaluable guidance, feedback, and encouragement throughout the research process. Finally, I would like to thank all my colleagues, past and present, at Skanska Teknik and the Department of Building Technology at Linnaeus University. Your support and collaboration have been greatly appreciated.

A special thanks goes to Per Finander (Saab) for developing the electronics used in this research. The successful monitoring of House Biologen was made possible by Anders Persson (Granitor) and Andreas Jakopson (Värends Entreprenad). The Skymningen Blocks project owes much to Henrik Berg (GBJ Bygg), and Fyrtornet to Måns Herner (Granitor) and André Lidholm (Byggnadsfirman Otto Magnusson). I also appreciate the contributions of the SBUF and KKS reference groups and their respective companies for their support in making this research possible.

Växjö, Sweden, November, 2025
Carl Larsson

Contents

Publications	xvii
List of appended papers	xvii
Authors contributions	xviii
Other publications	xix
1 Introduction	1
1.1 Background	1
1.2 Research aims and tasks	2
1.3 Thesis outline	3
2 Literature Review	5
2.1 The use of timber materials in modern construction	5
2.2 The use of concrete materials in modern construction	9
2.3 Timber-concrete hybrid buildings	11
2.4 Sources of uncertainty in structural design practice	13
2.5 Natural frequencies and mode shapes in codes	14
2.6 Vibration tests of buildings with structural members in timber . . .	15
2.7 Model updating of buildings with structural members in timber . .	16
3 Methodology	19
3.1 Case objects	20
3.2 Measurement systems	24
3.3 Structural Dynamics	30
3.4 Operational modal analysis	32
3.5 Finite Element Modelling of timber-concrete hybrid buildings . . .	35
3.6 Model Updating	37
3.7 Surrogate Models	40
4 Summary of appended papers	41
5 Conclusions & Future Work	51
5.1 Conclusions	51
5.2 Future work	52

References 53

Publications

List of appended papers

Paper I

Carl Larsson and Michael Dorn. A survey of the design of timber-concrete hybrid buildings in Sweden. In *Proceedings of World Conference on Timber Engineering (WCTE), June 19 – 22 2023, Oslo, Norway*. <https://doi.org/10.52202/069179-0565>

Paper II

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 III

Carl Larsson, Osama Abdeljaber and Michael Dorn. Dynamic evaluation of a nine-story timber-concrete hybrid building during construction. *Engineering Structures*, 2023, Volume 289. <https://doi.org/10.1016/j.engstruct.2023.116344>

Paper IV

Carl Larsson, Osama Abdeljaber and Michael Dorn. Dynamic testing and simultaneous model updating of two identical timber buildings with different substructures. *Engineering Structures*, 2025, Volume 339. <https://doi.org/10.1016/j.engstruct.2025.120557>

Paper V

Carl Larsson, Blaž Kurent, Osama Abdeljaber, and Michael Dorn. Multi-Stage Structural Identification of a Tall Timber Building during Construction: The Role of Connections and Non-Structural Elements. *Under review, submitted to Journal of Building Engineering*. Pre-print available at SSRN: <http://dx.doi.org/10.2139/ssrn.5416675>

Paper VI

Carl Larsson, Blaž Kurent, Osama Abdeljaber, Boštjan Brank, Michael Dorn. Recorded natural frequencies of timber buildings – A review. In *Proceedings of World Conference on Timber Engineering (WCTE), June 23 – 26 2025, Brisbane, Australia*. <https://doi.org/10.52202/080513-0309>

Authors contributions

Paper I

Carl Larsson: Conceptualization, Investigation, Writing – original draft. **Michael Dorn:** Supervision, Writing – review & editing.

Paper II

Carl Larsson: Conceptualization, Investigation, Writing – original draft. **Osama Abdeljaber:** Software, Data curation, Writing – review & editing. **Åsa Bolmsvik:** Supervision. **Michael Dorn:** Supervision, Writing – review & editing.

Paper III

Carl Larsson: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization, Funding acquisition. **Osama Abdeljaber:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – review & editing. **Michael Dorn:** Conceptualization, Supervision, Writing – review & editing, Funding acquisition.

Paper IV

Carl Larsson: Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Osama Abdeljaber:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michael Dorn:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Paper V

Carl Larsson: Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Blaž Kurent:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - Original Draft, Visualization. **Osama Abdeljaber:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michael Dorn:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Paper VI

Carl Larsson: Writing – original draft, Visualization, Validation, Data curation, Conceptualization. **Blaž Kurent:** Writing – original draft, Visualization, Validation, Data curation, Conceptualization. **Osama Abdeljaber:** Writing – review & editing, Supervision. **Boštjan Brank:** Supervision. **Michael Dorn:** Writing – review & editing, Supervision.

Other publications

Conference Proceedings I

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

Conference Proceedings II

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.

Conference Proceedings III

Ambrose Doodoo, Fatuma Omer Ali, Neda Bozorgirad, Felix Quarcoo and Carl Larsson. Life cycle carbon footprint analysis of cross-laminated timber multi-storey building: impact of material optimisation and substitution strategies. In *Proceedings of World Conference on Timber Engineering (WCTE)*, June 23 – 26 2025, Brisbane, Australia.

Conference Proceedings IV

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.

Conference Proceedings V

Carl Larsson, Osama Abdeljaber, and Michael Dorn. Case studies of timber-concrete hybrid buildings - Dynamic evaluations. In *12th In Forum Wood Building Nordic*, Växjö, Sweden, September 28 – 29, 2023.

Conference Proceedings VI

Carl Larsson. Following the Construction of Fyrtornet, by dynamic tests and model update. In *14th Forum Wood Building Nordic*, Malmö, Sweden, September 23 – 24, 2025.

Trade Publication I

Carl Larsson and Michael Dorn. Utvärdering av dynamiska egenskaper hos tre byggnader uppförda i KL-trä. In *Bygg & Teknik*, issue 4/24 pp 18-21, 2024.

1 Introduction

1.1 Background

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, 2024). As a significant contributor to climate change, the global construction industry shows growing interest in reducing 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). 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 is effective in reducing the environmental impact of buildings (Younis and Doodoo, 2022). In fact, the use of timber has become increasingly popular in recent years due to its sustainability and renewable nature.

However, this replacement is not without challenges. It is well known that buildings using timber have several difficulties due to the risk of fire (Bartlett et al., 2019), and biological risks (Wang et al., 2018), among others. For the load-bearing structure, timber has 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 fulfil (Landel, 2022), an issue for buildings as low as seven stories (Kurent et al., 2024b). A solution to fulfil the requirements of a modern building project is the introduction of timber-concrete hybrid buildings, where a combination of timber and concrete elements is used for the load-bearing structure.

In Sweden, the design of buildings has been subject to increased costs in recent years. One factor, highlighted by the industry through a report by Lindström and Lagerqvist (2015), is the implementation of the Eurocodes and Sweden's national application (EKS) in 2011, which has led to increased construction costs, particularly for concrete, steel, and timber structures, without a corresponding

perceived added value by the construction industry. The report highlighted that total construction costs rose by approximately 3%, and design costs by up to 10%. The complexity and volume of the new regulations have made them harder to apply and increased the risk of higher material usage, especially in multi-storey residential and office buildings.

Another study, performed by Fröderberg (2014), investigates how human factors, such as subjective judgment, limited knowledge, and inappropriate use of design tools, affect the efficiency of building design. Through interviews with practising engineers, the study highlights how decisions made under uncertainty can lead to inconsistencies and enhanced risk in structural engineering. Fröderberg emphasises the need for a better understanding and management of human influence in the design process. The findings suggest that improving communication, education, and decision-making frameworks can enhance cost-effectiveness in structural projects.

1.2 Research aims and tasks

With the growing interest in timber-concrete hybrid structures, the construction industry in Sweden recognised these issues with uncertainties and funded the research project presented in this thesis.

The research presented in this thesis aims to enhance the understanding of timber-concrete hybrid buildings and the use of these types of buildings within the construction sector. This overarching objective is pursued by evaluating and investigating the in situ performance of timber-concrete hybrid structures. The findings are intended to contribute to the development of design and construction methods for this relatively new building system.

To accomplish these objectives, four specific research tasks were formulated:

1. **Find, categorise, and understand structural design challenges involved in timber-concrete hybrid buildings in Sweden.** This task involved an interview study to identify industry-related research topics and categorise different types of timber-concrete hybrid structural systems used in Sweden.
2. **Perform in-situ measurements to evaluate the performance of buildings with characteristics from the timber-concrete hybrid definition.** This involves collecting data from actual buildings to understand their structural behaviour to evaluate the results in Task 4.
3. **Develop measurement systems for ambient vibration testing and operational modal analysis that are easy to use in timber-concrete hybrid buildings, both during production and when finished.** To complete Task 2 and Task 4, two different data acquisition systems were developed. The first system is designed for temporary measurements both during construction

and in finished buildings. The other system was developed for continuous and permanent use in finished buildings.

4. Evaluate measurement results using finite element models to investigate and evaluate parameters commonly assumed in a structural design process.

This task involves comparing experimental data with numerical models to understand the influence of various structural design parameters, such as material properties (e.g., moisture content, in-plane shear stiffness of CLT), element connections, soil-structure interaction, and non-structural walls.

The results and conclusions from this research work contribute to the general knowledge of timber-concrete hybrids' behaviour by addressing these tasks, particularly given that such building systems are relatively new to the market and in research.

1.3 Thesis outline

The introduction provided an overview of the research project, highlighting the research motivation, aim, and tasks. Chapter 2 presents a comprehensive literature review, highlighting topics such as the use of timber and concrete materials in today's modern construction. The literature review also highlights the human factor in structural design, including the different building codes, as well as similar research performed within the area. Chapter 3 presents the four studied timber-concrete hybrid buildings, the methods used in this thesis, including structural dynamics, measurement systems, FE modelling, and model updating. Chapter 4 provides an extended summary of the appended research papers. Chapter 5 finalises the thesis with conclusions and recommendations for further studies.

2 Literature Review

2.1 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 past centuries, large timber structures, particularly multi-storey buildings, were subject to strict regulations due to the risk of urban fires. As a result, materials such as stone and brick became the preferred choice for construction. Furthermore, the late 19th and early 20th centuries saw rapid development in alternative building materials, including steel and reinforced concrete. These developments contributed to a significant decline in the use of timber for large-scale construction projects. It was not until the 1990s that regulatory frameworks began to shift, allowing for renewed interest in timber as a viable building material.

Historic timber buildings that remain today are often celebrated for their exceptional craftsmanship and architectural integrity. Each timber log was carefully selected and shaped using traditional tools, such as saws and axes, demonstrating a deep understanding of both the material and the construction techniques of the time. While these structures reflect the nature of early timber construction, the timber industry has undergone a substantial transformation since then.

In recent decades, technological advancements have led to the development of a wide range of industrially processed timber products. These include beam elements such as sawn timber, glulam timber (GLT), and laminated veneer lumber (LVL), as well as plate elements like plywood, cross-laminated timber (CLT), and oriented strand board (OSB). Thanks to their low weight and high degree of prefabrication, these materials are easy to transport and quick to assemble on-site, making timber construction systems increasingly competitive with other building methods.

Moreover, advances in fire safety research have enabled the removal of earlier regulatory constraints that limited the size and scope of timber buildings. Material-based restrictions, such as limits on the number of storeys, have now been replaced by performance-based criteria. This regulatory shift, combined with the versatility and efficiency of modern timber products, has opened new possibilities for timber in construction.

2.1.1 Tree, wood, and timber

Material derived from trees has long been utilised in a wide range of applications. When used as a structural building material, this material is referred to as wood, which is classified as a homogeneous, cylindrical orthotropic material. This means that its mechanical properties differ depending on the direction in which they are measured. Wood has three principal material directions: longitudinal (L), radial (R), and tangential (T), as illustrated in Figure 2.1. These directions are defined based on the cross-section of a tree log, where growth rings and fibre orientation are visible.

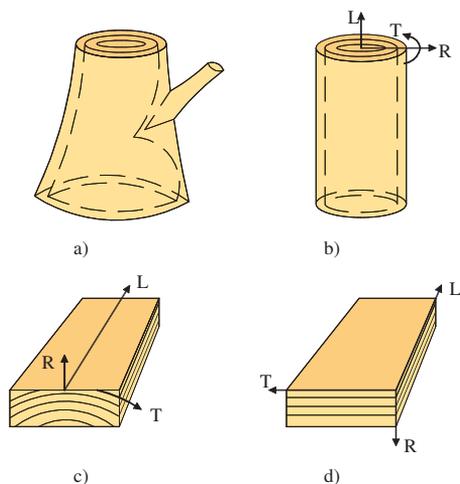


Figure 2.1: From a tree stem to a timber plank model: a) tree stem with natural growth characteristics, b) a cylindrical tree stem model and principal directions, c) sawn timber with its cylindrical principal directions, and d) an orthotropic model of timber planks. Images based upon Bodig and Jayne (1982).

The longitudinal direction L runs parallel to the stem and is typically the strongest and stiffest, as it aligns with the wood fibres. The radial direction R extends outward from the centre of the tree trunk, perpendicular to the growth rings, while the tangential direction T runs along the curvature of the growth rings. These directional differences are important because the mechanical and physical

properties of wood, such as strength, stiffness, shrinkage, and thermal conductivity, vary significantly between the three directions. This variation is primarily due to the cellular structure of wood at the microscopic level, which consists of elongated cells arranged in a highly organised pattern. However, it is important to highlight that, as a naturally grown material, timber exhibits non-homogeneous properties that cannot be fully controlled.

Once the tree is processed into usable elements, the sawn wood is referred to as timber. Timber is widely used in construction due to its favourable strength-to-weight ratio, ease of handling, and renewable nature. However, its anisotropic behaviour, growth irregularities and other potential weaknesses must be carefully considered when used in structural applications. Timber strength classifications are, for example, defined in EN 338 (European committee for standardization, 2016a), which specifies characteristic and mean values for different strength classes and is essential for structural design and material selection. Timber used in construction purposes for buildings is, for example, regulated in standards such as the Eurocode EC5 (European committee for standardization, 2011).

2.1.2 Moisture Content in Timber

Moisture in wood exists in two forms: free water, which is located within the lumens of wood cells, and bound water, which is contained within the cell walls. The moisture content (MC) of timber is defined as the ratio of the mass of water to the mass of oven-dried timber, and is usually expressed as a percentage (% MC). The MC during construction should correspond to the expected conditions during the building's service life to avoid negative consequences. Timber is therefore dried at the sawmills prior to further processing. During drying, free water is removed first, followed by a gradual reduction in bound water to a target MC of typically 10-14% MC .

The MC of timber is of great importance, as it significantly affects basically all properties of wood whereby strength and stiffness are of particular interest. Drying and rewetting also affect dimensional stability, potentially leading to crack formation. In addition, a high MC promotes the growth of fungi that degrade the timber. It is therefore essential to control MC accurately during both the construction and service phases of buildings to ensure reliable material performance. Environmental conditions can influence the MC of timber, and must be considered when classifying the material to ensure that its properties are determined correctly.

The strength and stiffness properties of timber generally decrease as the MC increases, whereas density tends to increase. A standardised method for determining reference properties from test data is provided in EN384 (European committee for standardization, 2016b). This standard enables accurate determination of reference properties, ensuring that the timber is suitable for structural applications:

$$f_{(c,0)} = f_{(c,0)}(u) \left(1 + 0.03(u - u_{ref}) \right) \quad (2.1)$$

$$E_0 = E_0(u) \left(1 + 0.01(u - u_{ref}) \right) \quad (2.2)$$

$$\rho = \rho(u) \left(1 - 0.005(u - u_{ref}) \right) \quad (2.3)$$

where $f_{(c,0)}$ is the compression strength parallel to the grain and E_0 the modulus of elasticity parallel to the grain. ρ 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 ρ .

2.1.3 Cross-laminated Timber

Cross-Laminated Timber (CLT) is a relatively recent innovation in the timber industry. It is an engineered wood product composed of an odd number of layers of timber boards, typically three to seven, as illustrated in Figure 2.2. Within each layer, the boards are arranged parallel to one another, while the adjacent layers are oriented perpendicular to one another. This crosswise arrangement results in a large timber plate element with excellent dimensional stability and high resistance to bending and deformation within its surface plane. CLT elements are commonly used as slab and wall components in modern construction.

The manufacturing process enables the production of large-format timber panels suitable for applications where precast concrete elements were previously used. The use of CLT has grown rapidly in recent years, driven by its numerous advantages, including improved structural performance, enhanced sustainability, and cost-effectiveness.

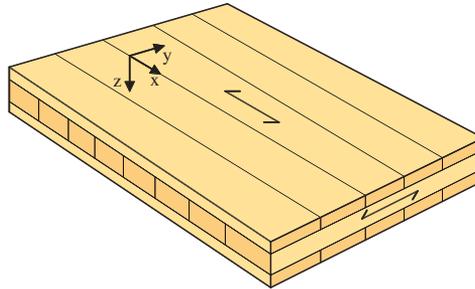


Figure 2.2: A 3d view of a 3-layer CLT element with principal directions of the element.

The technique of glueing layers of timber was first developed for plywood and laminated veneer lumber (LVL) in the early 1900s. In the 1990s, this method was adapted for use with solid timber boards, leading to the development of CLT. The first applications of CLT were introduced in Austria (Schickhofer, 1994) and

Germany, where it was also referred to as massive timber, X-lam, or Brettsperrholz (BSP). Two main glueing techniques are used in CLT production: non-edge-glued lamellas and edge-glued lamellas, both of which are available from different manufacturers. Additionally, a variant known as Nail Laminated Timber (NLT) uses mechanical fasteners instead of adhesives, although this type is relatively uncommon (Muszyński et al., 2020).

Following its introduction, several research projects were initiated, particularly at Graz University of Technology in Austria. Subsequent research and development continued in Germany and Switzerland. Around the year 2000, large-scale production of CLT began. By 2020, numerous CLT manufacturing plants were operating worldwide, primarily in Europe and North America, providing a substantial 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. 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.

Despite its many benefits, the use of CLT is still relatively new, and design provisions and standardisations 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 was first approved in 2015 (European committee for standardization, 2021). However, these guidelines are limited, and design provisions and product characteristics are still missing from the primary European standard for timber structures, Eurocodes EC5 (European committee for standardization, 2011). In the absence of comprehensive standardisation, 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).

2.2 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 utilised concrete in its buildings, many of which are 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 can also handle bending loads. The resulting material, known as reinforced concrete (RC), is commonly used for structural members in buildings, including beams, columns, slabs, walls, and in foundations. These elements can be either cast in situ on the building site or produced off-site as precast concrete elements. The use of RC 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 dates 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 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, which is primarily made of concrete and stands at 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.

2.2.1 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, as well as the standardisation of production methods for structural elements and fasteners. In addition, several innovations have enhanced the capabilities of precast concrete elements, such as the introduction of prestressing rebars, which have enabled 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.

2.3 Timber-concrete hybrid buildings

In this thesis, timber-concrete hybrid buildings are defined as buildings in which the structural system above the foundation level includes elements made of both timber and concrete. Such systems have gained popularity in recent years due to several advantages, including a reduced environmental footprint and the use of lightweight components compared to traditional construction methods. This thesis does not focus on structural elements that combine timber and concrete into a single unit, commonly referred to as timber-concrete composites. However, such elements may still form part of the overall load-bearing system.

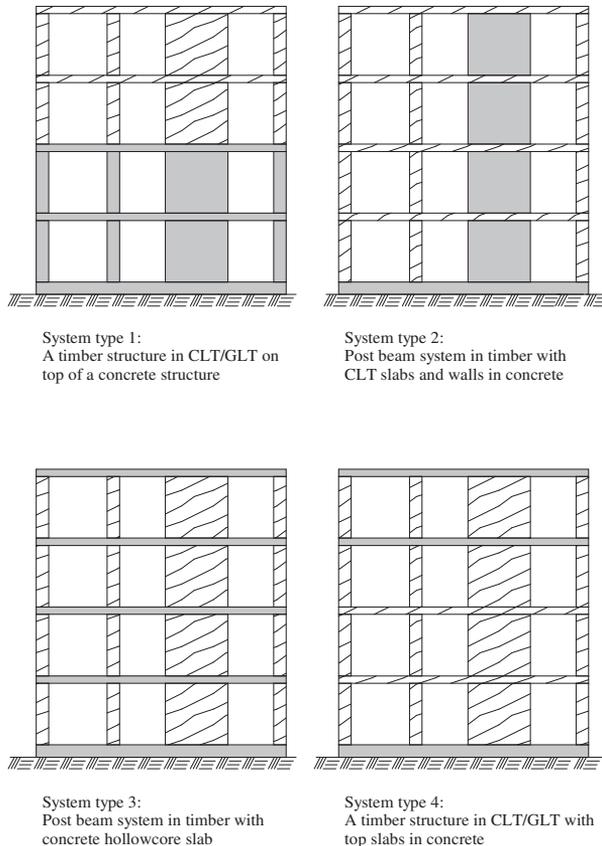


Figure 2.3: System types of the load-bearing structure in a timber-concrete hybrid identified in appended Paper I, where concrete members are in grey.

The definition was developed during the work for the appended Paper I, which involved studying various Swedish building projects that meet the criteria through

interviews. Four typical system types were identified, illustrated in Figure 2.3 and described as below:

- **System Type 1:** Common in residential buildings, where concrete storeys are included for uplift resistance or practical reasons, such as accommodating commercial spaces.
- **System Type 2:** Used in office buildings with a limited number of shear walls.
- **System Type 3:** Applied when longer slab spans are required, beyond what a CLT slab can provide.
- **System Type 4:** Used in taller buildings where additional mass is needed to meet dynamic performance requirements.

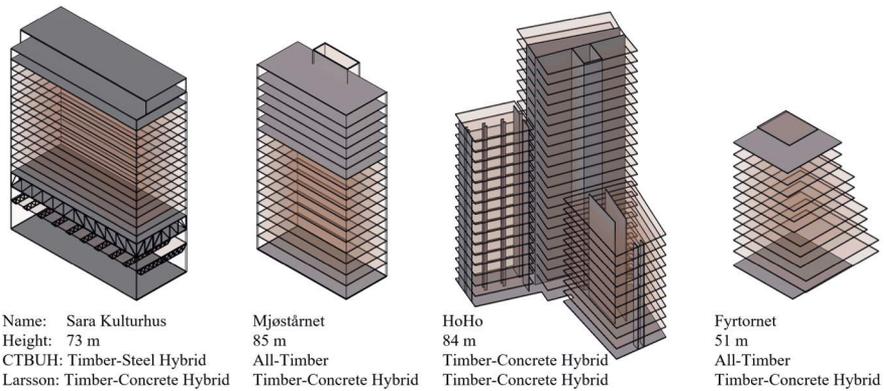


Figure 2.4: 3d-rendering of four tall timber-concrete buildings with timber elements in orange, concrete elements in grey, and steel elements in red. The definition, as provided by CTBUH, is also shown for comparison.

The Council on Tall Buildings and Urban Habitat (2022), CTBUH, which ranks tall timber buildings, has a different definition for timber and timber-hybrid buildings as it excludes concrete slabs from its definition. Mjøstårnet in Brumunddal, Norway, with a height of 85 metres, incorporated concrete slabs in the top seven storeys to increase self-weight (Abrahamsen, 2017), yet CTBUH classifies it as an all-timber building. Similarly, Sara Kulturhus in Skellefteå, Sweden, includes five storeys with concrete slabs and reaches a height of 73 metres (Skellefteå Kommun, 2021), which CTBUH categorises as a timber-steel hybrid. According to the classification framework adopted in this thesis, both buildings fall under System Type 4.

Another example is the HoHo Tower in Vienna, Austria, which is defined similarly in both this thesis and by the CTBUH. Figure 2.4 visualises and highlights these different buildings and definitions.

2.4 Sources of uncertainty in structural design practice

The design of timber buildings, particularly timber-concrete hybrid structures, is characterised by a less unified approach compared to buildings constructed with other traditional materials, according to the results in appended Paper I. A practising structural designer must be experienced at navigating these uncertainties. According to Melchers and Beck (2018), uncertainties in structural design can be broadly classified into four categories:

1. **Physical uncertainty** arises from the inherent randomness of a quantity. For example, the yield stress of a material may vary due to production variability.
2. **Measurement uncertainty** stems from imperfections in the measurement process, leading to inaccuracies in recorded data.
3. **Statistical uncertainty** is associated with the limited sample size of observed quantities, which can affect the reliability of statistical estimates.
4. **Model uncertainty** relates to the imperfect knowledge or simplifications inherent in mathematical models. It also includes uncertainty in the selection of probability distributions for stochastic variables.

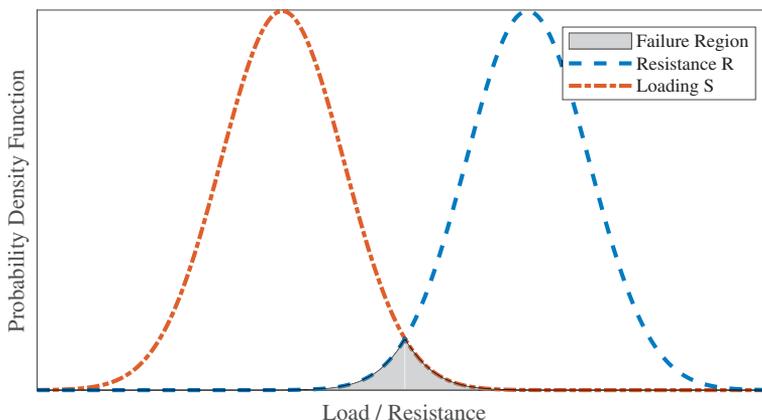


Figure 2.5: Example of Probability Density Functions where S is the load distribution applied on a structure and R is the structural resistance distribution. The grey area is the failure region where there is a risk of structural failure.

Today’s modern building codes consider these types of uncertainties. The Eurocodes in EC0 (European committee for standardization, 2002), use a partial coefficient system with a design equation as follows:

$$R_k/\gamma_R > (\gamma_G \cdot G_k + \gamma_Q \cdot Q_k) \cdot \gamma_d$$

where R is the resistance of the structural member. G and Q represent the dead loads and live loads acting on the structural member, respectively. To account for different uncertainties, partial safety factors, γ , are introduced. Different values are used for the loads and the structural resistance, such as strength and geometrical values for the structural member. The methodology is typically visualised in Probability Density Functions, as exemplified in figure 2.5.

The safety factors γ are calibrated to a target reliability index, called β . These can be found in JCSS Joint Committee on Structural Safety (2001). For example, a structural member with an Ultimate Limit Stage failure that poses a high risk of human fatalities, with a $\beta_{target} = 4.7$, yields a $\gamma_d = 1.0$.

However, Fröderberg (2014) demonstrated that despite the γ partial safety factor system used in the Eurocode, there was a significant uncertainty in the assumptions that each structural designer makes. This adds the human factor in structural design as an additional important uncertainty parameter. As found in the appended Paper I, this is especially important in timber-concrete hybrid buildings, where it was found that more structural designers are involved.

2.5 Natural frequencies and mode shapes in codes

Building codes commonly provide simplified equations for estimating the fundamental natural frequency of a structure, a key parameter in evaluating its dynamic behaviour. These equations are typically applied during the early design stages to generate preliminary estimates used in calculating wind loads and establishing criteria for sway accelerations. They may also be employed in the assessment of seismic loads.

Different building codes base their formulations on various empirical studies. As examples, the Eurocode, EC1-1-4, uses $f = 46/h$ whereas the American code, ASCE 7-2016, for taller buildings is $f = 150/(3.28h)$ for the first natural frequency. However, these studies have not been validated for timber structures or timber-concrete hybrid systems. Reynolds et al. (2016) conducted a state-of-the-art review encompassing 11 buildings incorporating timber elements, marking an initial effort to address this gap. This work was subsequently expanded upon in appended Paper VI and by Mohammadyzadeh and Zhou (2025b). A summary of the findings from these three studies is presented in Figure 2.6.

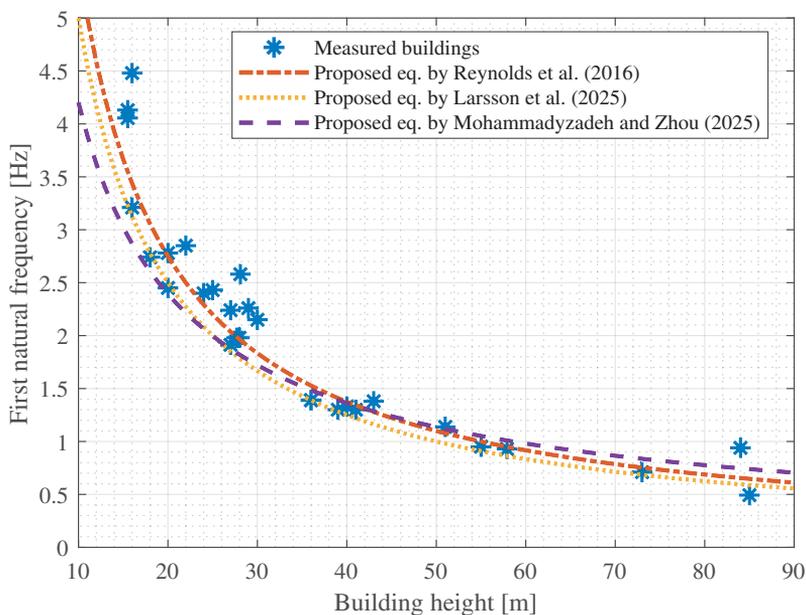


Figure 2.6: Summary of Vibration Tests of buildings using structural timber members along with proposed equations by Reynolds et al. (2016), Mohammadyzadeh and Zhou (2025), and appended Paper VI

2.6 Vibration tests of buildings with structural members in timber

Serviceability design challenges in taller timber buildings have been emphasised by several researchers, including Johansson et al. (2016) and Edskär and Lidelöw (2017). These challenges have led to increased academic attention and the launch of targeted research initiatives, such as DynaTTB, which aim to conduct vibration testing on buildings with structural members in timber (Abrahamsen et al., 2020).

In parallel with this growing research interest, the number of completed timber buildings available for testing has also risen. This has enabled both forced and ambient vibration tests to be carried out, with some studies also including long-term monitoring of the buildings' dynamic responses.

In Table 2.1, the latest published studies have been summarised where vibration tests have been performed. The results are also visualised in Figure 2.6 along with the predictions from the papers mentioned in Chapter 2.5.

Name	Height	1st freq.	Reference
Trinity	16 m	4.48 Hz	Kurent et al. (2023)
Not available	16 m	4.13 Hz	Reynolds et al. (2016)
Not available	16 m	4.06 Hz	Reynolds et al. (2016)
Charlie	17 m	3.21 Hz	Appended Paper II
Pilgatan	19 m	2.74 Hz	Amaddeo et al. (2024)
Terminus Building	20 m	2.78 Hz	Mohammadyzadeh and Zhou (2025a)
Univ. of East Anglia	21 m	2.45 Hz	Reynolds et al. (2014)
Yoker	22 m	2.85 Hz	Kurent et al. (2021)
Eken	24 m	2.40 Hz	Linderholt et al. (2024)
Skymningen	25 m	2.43 Hz	Appended Paper IV
Palisaden	27 m	1.88 Hz	Kurent et al. (2024a)
Limnologen	27 m	2.24 Hz	Reynolds et al. (2014)
Moholt	28 m	1.98 Hz	Tulebekova et al. (2023)
Biologen	28 m	2.58 Hz	Appended Paper III
Stadthaus	29 m	2.26 Hz	Reynolds et al. (2014)
Panorama 1	30 m	2.15 Hz	Tulebekova et al. (2023)
TreedIt	36 m	1.39 Hz	Manthey et al. (2021)
Panorama 2	39 m	1.30 Hz	Tulebekova et al. (2023)
The Vue Building	40 m	1.33 Hz	Hu and Auclair (2018)
Octivine	41 m	1.30 Hz	Mohammadyzadeh and Zhou (2025a)
Cederhusen	43 m	1.38 Hz	Pettersson and Edström (2024)
Treet	51 m	0.98 Hz	Olsen and Hansen (2016)
Fyrtornet	51 m	1.14 Hz	Appended Paper V
Brock Commons	54 m	0.94 Hz	Leishman et al. (2024)
Hyperion	56 m	0.95 Hz	Flamand et al. (2023)
Haut	73 m	0.71 Hz	Malaspina et al. (2023)
HoHo Tower	84 m	0.94 Hz	Appended Paper VI
Mjöstårnet	85 m	0.49 Hz	Tulebekova et al. (2022)

Table 2.1: Summary of vibration tests of buildings using structural timber members.

2.7 Model updating of buildings with structural members in timber

In addition to in-situ measurements of dynamic performance, several studies have employed model updating techniques in finite element (FE) models to improve the accuracy of structural simulations. Model updating refers to the process of refining an initial numerical model, which typically is based on design assumptions or simplified representations. Measurement data from the real building or structure is compared to the model's response, and the model assumptions are updated to better reflect the actual behaviour. This approach is particularly valuable in complex systems such as timber-concrete hybrid buildings, where uncertainties in material properties, boundary conditions, and connection behaviour can significantly affect dynamic response predictions.

During the literature review conducted for this thesis, two parameters emerged as particularly noteworthy due to the contrasting conclusions drawn across different studies: soil-structure interaction and timber element connections. While some studies suggest that soil-structure interaction plays a dominant role in altering the dynamic characteristics of buildings, others report minimal influence under certain conditions. Similarly, the modelling of timber connections, often complex due to their semi-rigid and non-linear behaviour, has led to varying interpretations regarding their impact on global stiffness and damping.

2.7.1 Soil-structure interaction

Soil-structure interaction in the analysis of buildings is generally considered by Winkler's supports for flat mat foundations. These supports are characterised by spring elements, making the implementation in FE models very simple.

However, it is well known that linear springs alone oversimplify the soil-structure interaction. In other engineering disciplines, such as railway bridge designs, the soil-structure interaction is often performed using 3d volumetric finite elements (Kamali, 2021). For buildings using piled supports, Winkler springs are not necessary as each pile can be simplified to a single spring element.

In the context of timber buildings, Winkler spring methods are frequently used, as shown in studies by Kurent et al. (2023), Kurent et al. (2021), and Manthey et al. (2021). It is also the method used in appended Papers III, IV and V.

On the other hand, several studies neglect the soil-structure interaction altogether. A rigid foundation was assumed, for example, in studies by Mugabo et al. (2019), Aloisio et al. (2020), Tulebekova et al. (2022), and Tulebekova et al. (2023).

2.7.2 Timber element connections

In an FE model, GLT members are typically modelled as beam elements and CLT members as shell elements. Connections are typically performed using node connectors for beam elements and line connectors for shell elements. Those connections may be implemented as rigid or hinged, alternately with a certain stiffness in the different directions.

Several studies have been conducted in this area, yielding different conclusions regarding the stiffness in such connectors. For example, Aloisio et al. (2020) concludes a negligible influence of connections in serviceability state design. On the other hand, Tulebekova et al. (2022), Tulebekova et al. (2023), and Landel and Linderholt (2022) highlight the importance of correctly modelled timber element connections with a certain compliance.

3 Methodology

This research aims to advance the understanding of timber-concrete hybrid buildings by integrating field measurements and evaluating design parameters. The methodology is structured around the research tasks 2, 3, and 4, each contributing to a comprehensive evaluation of the dynamic behaviour and design assumptions associated with timber-concrete hybrid buildings.

The following chapter includes a brief description of the methods used in the thesis, including the buildings used in case studies, the measurement systems used, as well as a brief theoretical background of structural dynamics, FE modelling, Operational Modal Analysis (OMA) and model updating. Figure 3.1 provides a graphical abstract for the thesis. The research tasks are visualized in a time-order with respect to the methods used in each.

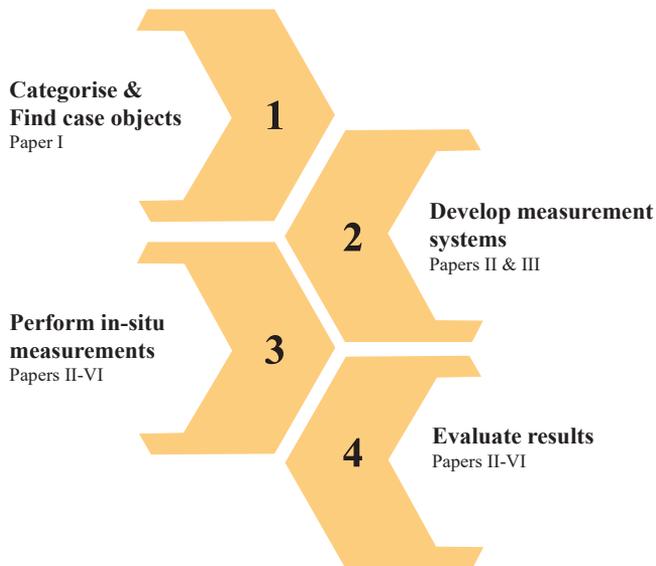


Figure 3.1: The research tasks visualised along with the appended papers.

3.1 Case objects

3.1.1 House Charlie

House Charlie, shown in Figure 3.2, is a four-storey office building located in Växjö, Sweden. The building comprises approximately 5,700 m² across four storeys, primarily consisting of office spaces, conference rooms, and supporting facilities. Construction was carried out between 2017 and 2018 by the contractor JSB AB, with Videum as the property developer. The building officially opened in September 2018 and is used as a case study in Paper II.

House Charlie measures 55 metres in length, 14.5 metres in width, and has a total height of 16 metres. The structural system consists of a GLT post-beam system with CLT slabs, supported by a concrete base plate. Lateral stability is provided by two precast concrete elevator shafts and steel bracings located on two façades. According to the classification framework presented in Figure 2.3, House Charlie is categorised as a System Type 2 building.

In addition to the structural system, there are non-structural facades in light-frame timber, non-structural walls with light-weight steel studs in the interior as well as a putty casting on top of the CLT slabs.

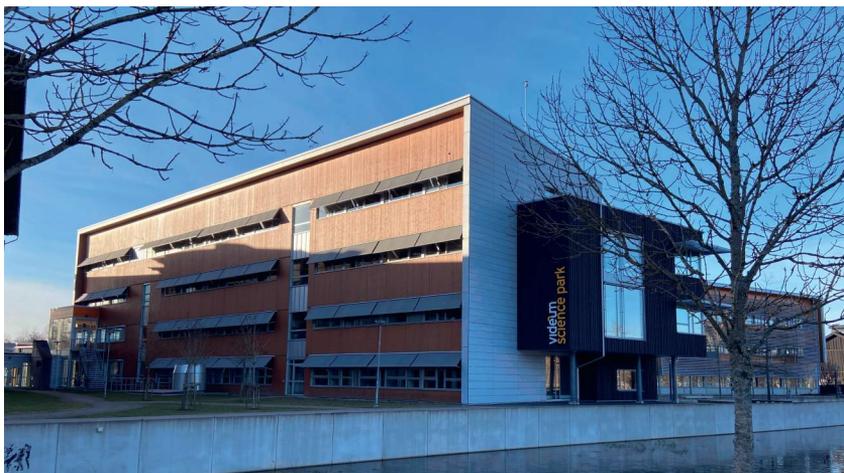


Figure 3.2: Photo of House Charlie

3.1.2 House Biologen 1

House Biologen 1, in Figure 3.3, is a nine-story residential building in Växjö, Sweden. The building accommodates a total of 70 apartments using four entrances with corresponding staircases. The building is 68 m in length, 13.5 m in width, and has a height of 28 m, having been constructed between 2021 and 2022. The building consists of a 3-7 story tall timber structure in CLT on top of a 2-story concrete structure and a concrete basement. The building is characterised by two higher sections, eight stories in the North and nine stories in the South. According to the classification framework presented in Figure 2.3, House Biologen 1 is categorised as a System Type 1 building. House Biologen 1 is used in Paper III.



Figure 3.3: Photos of House Biologen 1. a) and b) show the building during different stages of construction, and c) shows the finalised building.

3.1.3 The Skymningen Block

The Skymningen block consists of four buildings in total, located in Växjö, Sweden, and was completed in 2023. For the research project, two of these buildings were selected due to their identical timber structure. Both buildings are timber-concrete hybrid structures, categorised as a System Type 1 building according to this thesis, as shown in Figure 2.3. The Skymningen buildings are studied in Paper IV.

In both buildings, the first story consists mainly of cast-in-situ concrete with a height of 6 m, and the remaining four stories are in CLT with a total height of 19 m. The roof structure consists of timber trusses on top of a CLT slab, resulting in a total building height of 25 m. The footprint of the building is 520 m². House 1 consists of a single concrete story, whereas House 2 has an additional basement

story in the main part of the building. In addition, five concrete walls have been replaced with a precast post-beam system in House 2. The CLT structures in House 1 and House 2 on top of the concrete structures are identical.



Figure 3.4: Photos of House 1 in the Skymningen blocks, where a) is during construction and b) the finalised building.

3.1.4 Fyrtornet

Fyrtornet is a 51-meter-tall timber building completed in 2024. It is an 11-story office building located in Malmö, Sweden. The building, architecturally inspired by a lighthouse, is characterised by two slanting glass façades. The footprint of the building is $25.1 \times 25.1 \text{ m}$, but due to an inclined first story and the slanting façade, the floor area varies from $30.5 \times 30.5 \text{ m}$ to $22.7 \times 22.7 \text{ m}$. The building has a gross floor area of $9,010 \text{ m}^2$, which includes a timber superstructure area of $7,600 \text{ m}^2$, an underground basement area of 850 m^2 , and a terrace area of 560 m^2 .

The structural system of the building consists of a timber structure placed on an underground concrete basement story. The timber superstructure features elements made from GLT for the structural framework and CLT for the structural walls and slabs. The roof slab is done in concrete, which defines the structure as a timber-concrete hybrid, categorised as a system type 4 building according to Figure 2.3. The columns are arranged in a $4.8 \times 4.8 \text{ m}$ grid, to which the beams and slabs are attached. On the 2nd story, the grid extends 4.8 meters to the east and south, utilising cantilever beams supported by inclined columns.

The structural system for horizontal loads includes lateral bracings in GLT and shear walls in CLT, where the staircase and elevators are also placed. Horizontal loads are transferred to these structural members via the CLT slabs.



Figure 3.5: Photo of Fyrtornet. Photo provided by Granitor.

3.1.5 Other objects

In addition to the above-mentioned buildings, AVTs have been performed on three additional buildings. All three buildings are residential timber-concrete hybrid, categorised as a system type 1 building according to Figure 2.3. The first building is the 8-storey Limnologen building, finished in 2008 in Växjö, Sweden. The measurement of this building was used as a reference for the development of the mobile measurement system, as previous studies have been conducted by Reynolds et al. (2014).

The second building is the Cederhusen, a 13-storey residential building in Stockholm, Sweden. This was performed with two master's students as part of their master's thesis in collaboration with the Royal Institute of Technology in Stockholm. It is published in (Pettersson and Edström, 2024).

The third building is Vallen, a 9-storey residential building in Stockholm, Sweden. This was performed with two master's students as part of their master's theses at Linnaeus University, but it is currently not yet finished.



Figure 3.6: Photo of Cederhusen (left), Vallen (middle), and Limnologen (right). Photos provided by Larsson and Arkitektbolaget.

3.2 Measurement systems

In order to perform Operational Modal Analysis (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.

In the thesis, data from permanent and temporary individual measurement campaigns are evaluated. In this section, the different systems are briefly presented.

3.2.1 Development of a mobile system

For short-term monitoring, a mobile data acquisition system, shown in Figure 3.7 was developed in order to conduct the AVTs for the studies in appended Papers II-IV. The mobile data acquisition system was developed in collaboration with SAAB.



Figure 3.7: The left figure shows one of two prototypes of mobile data acquisition devices along with an initial plywood frame for the mounting of accelerometers. The right figure shows one of seven improved mobile data acquisition devices with a steel fixture for the mounting of accelerometers.

During the development of a mobile data acquisition system suitable for Operational Modal Analysis (OMA), several key requirements were identified early in the process. Firstly, the system must include all components required for collecting accelerometer data, comparable to those used in conventional wired systems. Secondly, it must allow multiple devices to operate in complete synchrony. Synchronisation is essential for OMA, where time-domain correlation is critical, and was therefore one of the main challenges. Thirdly, the system should be battery-powered and fully mobile, while providing sufficient runtime and ensuring that electrical interference does not compromise signal quality. Finally, the system should feature a user-friendly interface suitable for quick and efficient installation on building sites.

Two initial prototypes were developed (Figure 3.7, left), with their components shown in Figure 3.8. Extensive testing was conducted, including laboratory comparisons with a *DataPhysics DP700-60* Dynamic Signal Analyzer using identical setups and accelerometers, as well as full-scale tests on buildings with known natural frequencies. These included House Charlie, equipped with a fixed acquisition system, and Limnologen, previously investigated by (Reynolds et al., 2014). The prototypes were also used for initial measurements in House Biologen (Paper III).

Subsequently, an improved version was developed (Figure 3.7, right). While maintaining the core functionality, this version addressed software issues, reduced noise, improved handling, allowed for three channels per unit, and introduced a more intuitive interface for faster deployment. Additional features enabled fixed installations, for e.g. laboratory use. In total, seven upgraded units were produced, supporting up to 21 accelerometers. These systems were employed in later measurements at House Biologen, Skymningen, and Fyrtornet, as reported in appended Papers III–V.

3.2.2 Permanent installation

3.2.2.1 Permanent installation at House Charlie

In appended Paper II, 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 include combined temperature/humidity sensors, accelerometers, 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 involved in the development of this system, as it was installed in House Charlie before he

began his PhD 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.

In House Charlie, 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 analogue-to-digital converter (ADC) was connected. Each ADC card (Figure 3.9) has four inputs in total. Each input is equipped with a digital filter, a sample/hold amplifier, and a 24-bit A/D converter. Additionally, a separate circuit board was added to amplify the geophone output by approximately 500 times. The ADC is powered by a Power over Ethernet (PoE) splitter.

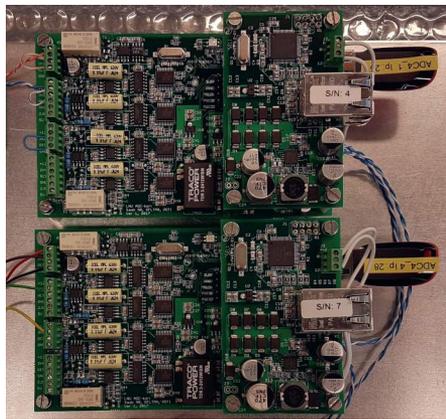


Figure 3.9: Picture of two ADC cards used for the measurements in House Charlie.

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 enables remote control of the system and allows downloading of the data.

The interval of the recordings could easily be changed during the monitoring period through the server. Additionally, readings from one sensor can 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.

3.2.2.2 Permanent installation at Fyrtornet

In Fyrtornet, another permanent installation of a measurement system was performed in late 2024. A GSM router enables data access, whilst control and data storage are done on a Raspberry Pi.

Two accelerometers were attached to the top CLT slab in the northeast corner to record the first two modes. The data is then stored on a Data Acquisition Device (Digilent, 2025). For hygrothermal data, a similar system as in House Charlie was also installed in House Fyrtornet. This data is collected at three locations: indoor climate, moisture content in a CLT slab and moisture content in a GLT beam. Figure 3.10 shows the installation of the system in late 2024.



Figure 3.10: Photo during installation of the permanent system in 2024 at Fyrtornet with Michael Dorn.

3.2.3 Sensors

3.2.3.1 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 3.11 shows an illustration of a geophone. The geophone used in this thesis is the PS-4.5B from Sunfull.

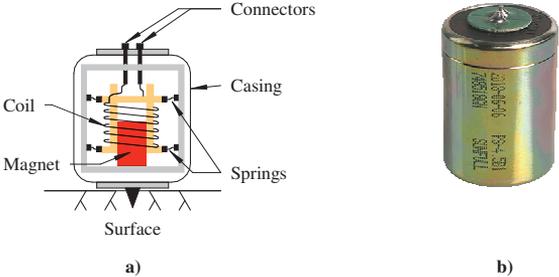


Figure 3.11: a) Illustration of the components in a geophone, and b) the Sunfull PS-4.5B used for the fixed data acquisition system.

3.2.3.2 Accelerometers

Accelerometers are another type of vibration sensor, differing from geophones in that their output signal is proportional to acceleration. These sensors typically employ piezoelectric crystals positioned between a seismic mass and a fixed base. When the sensor experiences motion, the mass exerts a force on the crystal, causing deformation and generating a voltage proportional to the applied acceleration. Figure 3.12 illustrates the working principle of an accelerometer, along with the PCB393B12 model from PCB used in this thesis.

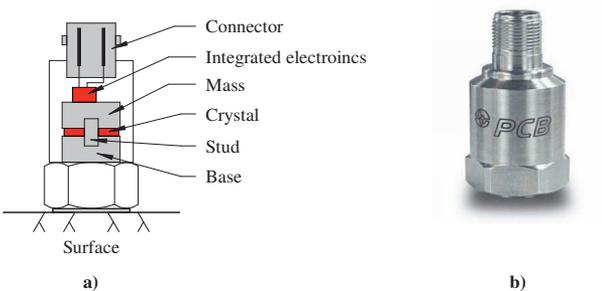


Figure 3.12: a) Illustration of the components in an accelerometer, and b) the PCB393B12 used for the mobile data acquisition system.

3.2.3.3 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.

3.3 Structural Dynamics

In the appended papers II-VI, dynamic measurements are performed. The basics of structural dynamics are explained in the following section.

3.3.1 Single-degree-of-freedom systems

In structural dynamics, the single-degree-of-freedom (SDOF) system serves as a fundamental model for understanding the dynamic behaviour of structures. It represents the simplest form of a dynamic system, consisting of a concentrated mass m , a linear spring with stiffness k , and a damper with damping coefficient c . The system is characterised by a single displacement variable $u(t)$, which describes the motion of the mass over time.

The equation of motion for the system given in Figure 3.13 can be described in the time domain by the following second-order differential equation:

$$m\ddot{u} + c\dot{u} + ku = F(t) \quad (3.1)$$

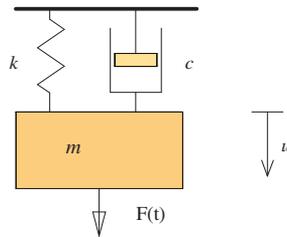


Figure 3.13: A single-degree-of-freedom system illustrated.

For an undamped system under free vibration, where the force $F(t)$ and damping c equals 0, equation 3.1 simplifies to the following:

$$m\ddot{u} + ku = 0 \quad (3.2)$$

The general solution of this homogeneous equation can be expressed as a sinusoidal function:

$$u = C \sin(\omega t + \alpha) \quad (3.3)$$

where:

$$C = \sqrt{u_0^2 + \left(\frac{v_0}{\omega}\right)^2}, \quad \alpha = \arctan\left(\frac{u_0 \omega}{v_0}\right) \quad (3.4)$$

Here, u_0 and v_0 are the initial displacement and velocity, respectively. Substituting Equation 3.4 into Equation 3.3 yields the following expression for the undamped natural frequency ω of the SDOF system:

$$\omega = \sqrt{k/m} \quad (3.5)$$

The damping ratio ζ is a dimensionless parameter that describes how the energy of the oscillating mass dissipates over time. It can be calculated as follows:

$$\zeta = \frac{c}{2\sqrt{mk}} = \frac{c}{c_r} \quad (3.6)$$

A damping ratio ζ less than 1 indicates an underdamped system, while $\zeta = 1$ corresponds to a critically damped system, and $\zeta > 1$ represents an overdamped SDOF system. The damped natural frequency can be calculated given ζ and the natural frequency ω of the corresponding undamped system:

$$\omega_d = \omega \sqrt{1 - \zeta^2} \quad (3.7)$$

In practice, buildings are always underdamped with small damping ratios (typically less than 5%), meaning that their damped natural frequency is nearly equal to the undamped natural frequency.

3.3.2 Multi-degree-of-freedom systems

The motion of a linear multi-degree-of-freedom (MDOF) system with n DOFs can be expressed by the following matrix differential equation:

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{F}(t) \quad (3.8)$$

where \mathbf{u} is the displacement vector, \mathbf{F} is the force vector, and \mathbf{M} , \mathbf{C} , and \mathbf{K} are the mass, damping, and stiffness matrices, respectively. For an undamped system under free vibration, the equation of motion is:

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{0} \quad (3.9)$$

Assuming a harmonic solution in the form $\mathbf{u}(t) = \varphi \sin(\omega t + \alpha)$ and substituting that into Equation 3.9 yields the following:

$$(\mathbf{K} - \omega^2 \mathbf{M})\boldsymbol{\varphi} = \mathbf{0} \quad (3.10)$$

Solving this eigenvalue problem provides the n undamped natural frequencies ω_i as well as the corresponding mode shapes $\boldsymbol{\varphi}_i$, which form the modal matrix $\boldsymbol{\Phi}$.

The mass and stiffness matrices of a building can be estimated from its geometry and material properties (i.e., stiffnesses and densities) of its structural elements. Methods such as FE analysis can be used for this purpose. However, the damping properties of different structural materials, members, and especially connections are not well established. Therefore, Rayleigh damping is commonly used as an idealisation for simplifying the calculation of the damping matrix in terms of the mass and stiffness matrices:

$$\mathbf{C} = a_0 \mathbf{M} + a_1 \mathbf{K} \quad (3.11)$$

where a_0 and a_1 are the mass-proportional and stiffness-proportional damping coefficients, respectively. The damping ratio of the i^{th} mode can then be calculated as follows:

$$\zeta_i = \frac{a_0}{2\omega_i} + \frac{a_1 \omega_i}{2} \quad (3.12)$$

3.4 Operational modal analysis

Operational Modal Analysis (OMA) is a widely used technique in structural engineering for identifying the modal properties of structures subjected to ambient excitation. OMA relies on measurements from sensors such as accelerometers or geophones to capture the dynamic response of the structure. These measurements are then processed using models to identify key modal parameters, including natural frequencies, damping ratios, and mode shapes (Brincker, 2015).

A primary advantage of OMA is that it is an output-only identification technique, meaning the excitation forces acting on the structure are unknown. For buildings, these unknown excitations typically originate from ambient sources such as wind and traffic. This enables in-situ ambient vibration testing without the need for controlled excitation (e.g., from a shaker), by recording the structural response to naturally occurring forces.

OMA is based on the assumption that the unknown excitation can be modelled as broadband white noise over the frequency range of interest. White noise is characterised by a flat power spectral density, indicating equal energy distribution across all frequencies. This assumption is critical because it ensures that all modes are sufficiently excited. However, the assumption does not hold in cases where the excitation is dominated by narrowband or periodic components, such as vibrations induced by rotating machinery or elevators. In such cases, the excitation cannot be

approximated as broadband, and the fundamental assumption of OMA is violated, rendering the method unsuitable.

The OMA procedure consists of several steps, which are illustrated in Figure 3.14 and described briefly in the following subsections.

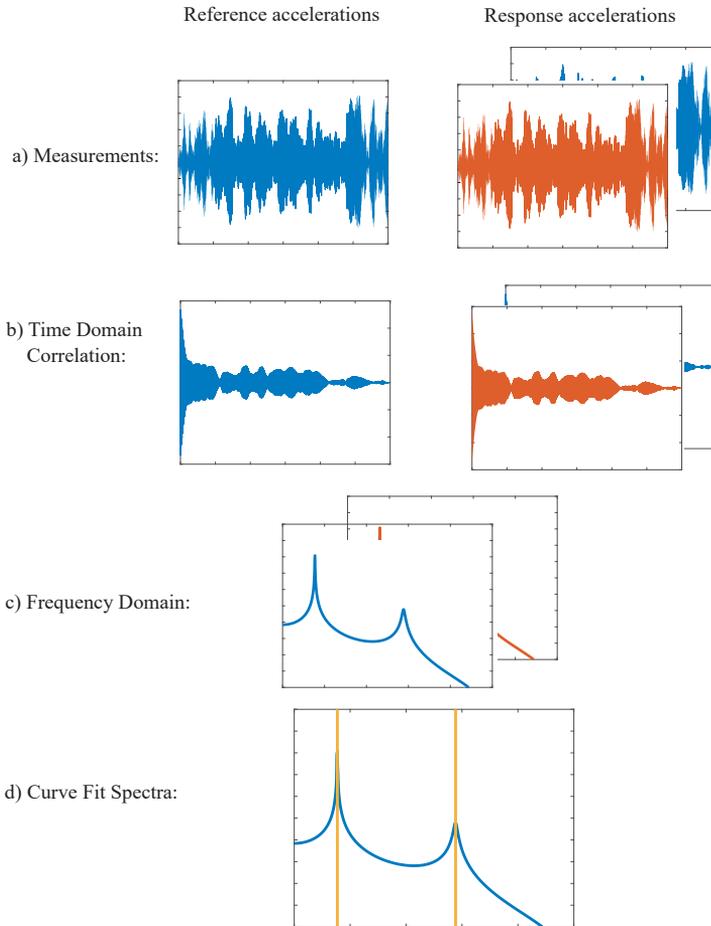


Figure 3.14: OMA is explained in four steps where: a) is the measured accelerations, b) time domain correlation using auto-correlation and cross-correlation functions, c) the Fourier transform performed on the correlated data, and d) the curve fit spectra.

3.4.1 Data acquisition

The acquisition of data involves gathering time-stamped acceleration data from one or more locations on the structure. The recording duration must be long

enough to capture the relevant dynamic characteristics, which are influenced by the structure's size and modal frequencies.

The acquisition system must also cover a sufficiently wide frequency range. For buildings, with frequencies reaching below 1 Hz, the lower range is a challenge since accelerometers often are optimised for much higher frequency ranges. The sampling frequency must be substantially higher than the building's expected frequency to achieve proper signal resolution.

As shown in Figure 3.14a, the raw acceleration signals typically appear as random scatter in the time domain, with no immediately discernible patterns.

3.4.2 Data processing

In the first step of data processing, statistical tools are applied in the time domain to compute autocorrelation and cross-correlation functions. These functions reveal the system's dynamic characteristics by comparing signals at different time lags: autocorrelation for signals from the same sensor, and cross-correlation for signals from different sensors. The resulting correlated data, shown in Figure 3.14b, contains periodic components associated with the structure's natural modes.

The second step of data processing can be divided into two main categories of evaluation methods: frequency-domain methods and time-domain methods. Both aim to identify the same modal parameters, but they differ in how the measured data is processed.

Frequency-domain methods, such as Frequency Domain Decomposition (FDD) and Enhanced FDD (EFDD), compute auto- and cross-correlation functions and then apply the Fast Fourier Transform (FFT) to obtain Power Spectral Density (PSD) matrices. These functions reveal the system's dynamic characteristics by comparing signals at different time steps, autocorrelation for the same sensor and cross-correlation for different sensors. The resulting correlated data, shown in Figure 3.14b, contains periodic components associated with the structure's natural modes. These matrices are analysed using techniques such as Singular Value Decomposition (SVD) to identify resonant frequencies and mode shapes. EFDD further estimates damping by performing an inverse FFT on selected frequency bands.

Time-domain methods such as Stochastic Subspace Identification (SSI) operate directly on the time-series data without transforming it into the frequency domain. SSI constructs a state-space model from the measured outputs using subspace projection techniques and estimates the system matrices via least squares. Modal parameters are then extracted from the eigenvalues and eigenvectors of the state matrix. In this work (Papers III–V), the SSI method was employed using Artemis Modal (A/S, 2022), which is a specialised modal analysis software.

It is important to note that because OMA does not measure or assume the input forces, the identified mode shapes are unscaled. This limitation arises

because the correlation-based approach normalises the output signals, allowing only the determination of relative mode shapes. Consequently, OMA cannot predict absolute structural responses (e.g., displacements or accelerations) under a specific known load. For such cases, Experimental Modal Analysis (EMA) must be used. EMA applies a known excitation (e.g., via a shaker) and measures both input and output, enabling the computation of scaled mode shapes and absolute response predictions.

3.4.3 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 Φ_x from a FEA and Φ_y from an OMA, the MAC can be calculated according to Equation 3.13.

$$MAC_{x,y} = \frac{(\Phi_x^T \Phi_y)^2}{(\Phi_x^T \Phi_x)(\Phi_y^T \Phi_y)} \quad (3.13)$$

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.

3.5 Finite Element Modelling of timber-concrete hybrid buildings

Structural dynamic modal analysis on full-scale buildings is often performed using numerical methods. FE Analysis is a valuable tool since it is used to characterise the mass and stiffness of different structural system types. In an FEA, a global mass and stiffness matrix is computed from the geometry and material properties of the included structural elements. With knowledge of the structural system's global mass (\mathbf{M}) and stiffness (\mathbf{K}) matrices, a modal analysis can be performed according to the following steps to calculate the natural frequencies and the corresponding mode shapes.

3.5.1 Element types

In the thesis and the appended papers, GLT members are modelled as beam elements, and CLT members are modelled as shell elements. Concrete elements, such as slabs and walls, are also modelled using shell elements.

3.5.2 Material Models

3.5.2.1 Timber material model

The constitutive model used for timber is a linear-elastic orthotropic material model expressed in an L-R-T system (see fig. 2.1). In a FEA, the constitutive model can be described by Hooke's law in Equation 3.14:

$$\sigma = \mathbf{D}\varepsilon \quad (3.14)$$

where σ is the stress tensor, \mathbf{D} is the material elasticity tensor in matrix notation and ε the elastic strain tensor. Equation 3.15 gives the constitutive equation expressed in matrix notation, using the principal material directions L-R-T given in Figure 2.1.

$$\underbrace{\begin{bmatrix} \sigma_L \\ \sigma_T \\ \sigma_R \\ \tau_{LT} \\ \tau_{LR} \\ \tau_{TR} \end{bmatrix}}_{\sigma} = \underbrace{\begin{bmatrix} \frac{1}{E_L} & -\frac{\nu_{TL}}{E_T} & \frac{\nu_{RL}}{E_R} & 0 & 0 & 0 \\ -\frac{\nu_{LT}}{E_L} & -\frac{1}{E_T} & -\frac{\nu_{RT}}{E_R} & 0 & 0 & 0 \\ -\frac{\nu_{LR}}{E_L} & -\frac{\nu_{TR}}{E_T} & \frac{1}{E_R} & 0 & 0 & 0 \\ & & & \frac{1}{G_{LT}} & 0 & 0 \\ & & & & \frac{1}{G_{LR}} & 0 \\ & & & & & \frac{1}{G_{TR}} \end{bmatrix}^{-1}}_{\mathbf{D}} \underbrace{\begin{bmatrix} \varepsilon_L \\ \varepsilon_T \\ \varepsilon_R \\ \gamma_{LT} \\ \gamma_{LR} \\ \gamma_{TR} \end{bmatrix}}_{\varepsilon} \quad (3.15)$$

While the model in Equation 3.15 is used for solid elements in a FEA, CLT is usually modelled 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 3.16. 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, several reduction factors are introduced ($k_{33} - k_{55}$ and k_{88}), as the CLT plate cannot be considered 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, as given in Equation 3.16, can be either provided by producers or obtained from handbooks, such as the Swedish CLT Handbook (Gustafsson et al., 2019).

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \\ V_x \\ V_y \\ N_x \\ N_y \\ N_{xy} \end{bmatrix} = \begin{bmatrix} D_{11} & D_{12} & 0 & 0 & 0 & 0 & 0 & 0 \\ & D_{22} & 0 & 0 & 0 & 0 & 0 & 0 \\ & & k_{33}D_{33} & 0 & 0 & 0 & 0 & 0 \\ & & & k_{44}D_{44} & 0 & 0 & 0 & 0 \\ & & & & k_{55}D_{55} & 0 & 0 & 0 \\ & & sym. & & & D_{66} & D_{67} & 0 \\ & & & & & & D_{77} & 0 \\ & & & & & & & k_{88}D_{88} \end{bmatrix} \begin{bmatrix} \kappa_x \\ \kappa_y \\ \kappa_{xy} \\ \gamma_x \\ \gamma_y \\ \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix} \quad (3.16)$$

3.5.2.2 Concrete material model

For concrete elements, an isotropic linear elastic material model was used. The model can be described as follows:

$$E = 2G(1 + \nu) \quad (3.17)$$

where E is the Modulus of Elasticity, G the shear modulus and ν the Poisson's ratio.

3.5.3 Convergence Analysis

Convergence analysis is performed to determine an appropriate mesh size for FE models, ensuring a balance between accuracy and computational efficiency. In the appended Papers II-V, an appropriate mesh size has been around 0.3m.

3.6 Model Updating

Model updating is a fundamental procedure that aims to refine numerical models so that their predicted responses align with experimental observations. Initial models often rely on assumptions regarding material properties, boundary conditions, and geometry, which can introduce discrepancies between the simulated and the actual behaviour. By systematically adjusting model parameters, model updating improves predictive accuracy and ensures the model's reliability for design, assessment, and structural health monitoring.

In the context of structural dynamics, model updating commonly utilises data from dynamic testing. Modal parameters such as natural frequencies and mode shapes, identified through OMA, are compared with those predicted by the FE model. Discrepancies are minimised through iterative calibration of properties such as stiffness and mass distribution. This process is essential for validating models where an accurate representation of dynamic characteristics is necessary.

Model updating is usually performed in the following steps:

1. Initial creation of a numerical model

A numerical model of the building is initially created. The model parameters, such as material properties, connection stiffness, and foundation characteristics, are assigned based on reasonable first approximations within expected ranges.

2. Ambient Vibration Testing and OMA

The building is investigated through one or more AVTs to capture its dynamic behaviour. The recorded data are then processed and analysed using OMA.

3. Error quantification

The results from the initial model (Step 1) are compared with the measured data obtained from Step 2. For a given parameter set \mathbf{p} , Equation 3.18 quantifies the error between the measured (f_i^{exp}) and calculated (f_i^{FE}) frequencies and Equation 3.19 compares the mode shapes, where ϕ_i^{exp} is the measured mode shape and ϕ_i^{FE} is the calculated one. These equations serve as objective functions, and their values are compared against predefined threshold criteria. If the error is sufficiently small, the procedure is terminated, and the parameter set \mathbf{p} is accepted as final. Otherwise, the loop continues with Step 4.

$$\delta_{\text{freq},s} = \sum_{i=1}^{M_s} \left| \frac{f_i^{\text{FE}}(\mathbf{p}) - f_i^{\text{exp}}}{f_i^{\text{exp}}} \right| \quad (3.18)$$

$$\delta_{\text{MAC},s} = \sum_{i=1}^{M_s} (1 - \text{MAC}(\phi_i^{\text{FE}}(\mathbf{p}), \phi_i^{\text{exp}})) \quad (3.19)$$

4. Update the model

The model parameters are updated using a suitable model updating technique, and the error metrics from Step 3 are recalculated. This iterative process continues until the errors fall below the defined thresholds.

A variety of model updating techniques can be found in the literature for updating FE models and comparing them to the results from an OMA. The most basic technique is the *Trial and Error* method, where parameters are manually updated based on the user's experience and input, or simply by evaluating the parameters within their full range (Halab-Kessira and Ricard, 1999). Other methods employ different types of mathematical expressions to predict the order in which the various parameters are evaluated.

Gradient-based optimisation methods are classified as local optimisation techniques, meaning they typically converge to an optimum near the initial starting point, without guaranteeing a global solution. These methods rely on the derivative of the objective function to determine the direction of steepest descent, guiding the search towards optimal parameter values. They are generally efficient, requiring

Building	Optimisation Method	Reference
Yoker	Bayesian Updating	Kurent et al. (2024b)
Trinity	Bayesian Updating	Kurent et al. (2024b)
Palisaden	Bayesian Updating	Kurent et al. (2024b)
Panorama 1	Trial and error	Tulebekova et al. (2023)
Panorama 2	Trial and error	Tulebekova et al. (2023)
Mjøstårnet	Genetic Algorithm	Tulebekova et al. (2023)
Biologen	Trial and error	Appended Paper III
Skymningen	Particle swarm optimisation	Appended Paper IV
Fyrtornet	Genetic Algorithm	Appended Paper V

Table 3.1: Comparison of different types of Parameter Updating methods used in similar model updating studies of timber buildings or timber-concrete hybrid buildings

relatively few function evaluations when gradients are readily available. However, they are sensitive to the initial conditions and may become trapped in local minima, potentially missing the global optimum.

Global optimisation methods aim to explore the entire design space to identify the best possible solution, rather than converging to a local optimum. These methods are particularly suited for complex problems where multiple local minima exist, making traditional local approaches insufficient. *Population-based optimisation algorithms* operate on a population of candidate solutions simultaneously, evolving them over successive iterations to improve performance. An example of such algorithms is *Genetic algorithms*, which mimic the process of natural selection by applying operations such as mutation, crossover, and selection on the population of solutions. Genetic Algorithms are effective for solving complex, multi-modal problems, but they can be computationally demanding and require careful tuning of algorithm parameters.

Another widely used method is *Particle Swarm Optimisation (PSO)*, inspired by the collective behaviour of animals and insects. PSO is particularly suitable for continuous-variable problems and is relatively easy to implement, requiring only a few parameters. It does not rely on gradient information, making it robust for non-linear, noisy, or discontinuous optimisation problems.

Finally, there is the *Bayesian method*. The core principle of this approach is to treat uncertainty in model parameters and modelling errors as random variables. These uncertainties are described using probability density functions, allowing for a probabilistic formulation of the model updating process. Bayesian inference is then used to update the probability distributions based on observed data, resulting in a posterior distribution that reflects both prior knowledge and experimental evidence.

For model updating of timber-concrete hybrid structures, various methods have been employed in the literature, as shown in Table 3.1.

3.7 Surrogate Models

A major challenge in model updating lies in the computational cost of evaluating the objective function, particularly when the FE models are large and complex. Each evaluation may take several minutes, and as previously described, global optimisation algorithms often require thousands of evaluations to converge. This makes direct optimisation using full FE models impractical.

In the appended Paper IV, the traditional methods for modal analysis using FE models were replaced with a surrogate model.

A surrogate model is a data-driven approximation that mimics the input–output behaviour of a structural model, but with significantly reduced computational cost. These models are simplified representations of complex numerical simulations. In structural engineering, surrogate models are increasingly used to facilitate optimisation, sensitivity analysis, and uncertainty quantification (Forrester et al., 2008). According to Samadian et al. (2024), the procedure typically involves the following steps:

1. **Define Design Parameters**

Identify the key design parameters that influence the structural response. These parameters serve as inputs to the surrogate model and are defined over a specified range.

2. **Database Generation**

Perform FE analyses for a representative set of cases by sampling the design parameters across their full range. Store the resulting outputs along with the corresponding input values to form a training dataset.

3. **Surrogate Model Fitting**

Construct a surrogate model that maps the input parameters to the output responses using the training dataset.

The surrogate model used in the appended Paper IV of this thesis is a neural network. Neural networks are a class of machine learning models inspired by the structure of the human brain, designed to recognise patterns and approximate complex, non-linear functions (Bishop and Nasrabadi, 2006). They consist of interconnected layers of nodes (neurons) that process input data through weighted connections and activation functions. The input layer represents the design parameters under investigation, while the output layer provides the predicted natural frequencies and corresponding mode shapes. The internal structure includes one or more hidden layers, which contain the neurons responsible for learning the mapping between inputs and outputs. In the appended Paper IV, a single hidden layer with ten neurons was used.

4 Summary of appended papers

Paper I

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

Relation to research tasks: Task 1: *Find, categorise, 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 study was performed during autumn 2020, and ten different building projects in Sweden were identified. For these ten projects, interviews with 18 stakeholders, such as property developers, contractors, and structural designers, were performed.

The term timber-concrete hybrid building was defined, and the studied projects were grouped into four different types of timber-concrete hybrid structural systems, which are also described in the chapter 2.3 of this thesis. Developers motivated the increased use of timber in response to changing demands from within the construction sector, municipalities, architects, and society in general. The favourable environmental footprint of timber was given as the main reason behind this.

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

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

Paper II

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

Relation to research tasks: Task 3: *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, categorised as a system type 2 building in this thesis. A previous research group consisting of Bolmsvik, Klaesson, Enquist, Brandt, and Finander performed the installation of the monitoring system in the building. The system incorporates dynamic measurements using geophones, hygrothermal measurements utilising relative humidity and temperature sensors, as well as displacement transducers. A weather station was used to collect exterior temperature and humidity, wind speed and wind direction, and solar radiation affecting the building. The recordings began in July 2018 and were evaluated until September 2021, spanning approximately three years.

The OMA, performed on the geophone data, showed three clear mode shapes of the building with corresponding natural frequencies and damping. The natural frequencies exhibited a seasonal variation, with the highest values recorded during September/October, and the lowest during March and April, e.g., the first natural frequency varied 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 relative humidity and temperature readings were recalculated to determine the MC in timber elements. The analysis of the MC in a CLT slab element located on the first floor of the building revealed a similar seasonal pattern to that of the natural frequencies. The readings showed that the MC 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 relatively constant due to the cooling during summer and heating during winter, also in the thickness direction.

A correlation analysis between the MC in the CLT slab and the recorded natural frequencies for the entire building revealed a clear positive correlation, with correlation coefficients ranging from $R^2 = 0.81$ to 0.84. This is particularly interesting since the governing structural elements for lateral stability are built in other materials (concrete shear walls and steel bracings in the façade), which are not equally influenced by seasonal variation.

Finally, a model was developed to predict the moisture content within the CLT plate, based on the previously measured values over three years. The following parameters were introduced for the model:

1. Dry-out: The wood material is assumed to dry out over time, up to a point where it is in equilibrium with the surroundings. This is of particular interest as the timber arrives with a higher moisture content from production and may have excess water from the building site. The interior humidity conditions are usually relatively dry for office buildings.
2. Seasonal variation: As the relative humidity level in the surroundings varies over the year, a second variable is introduced describing these seasonal variations. This variation is assumed to occur annually and does not show a reduction over time.
3. Long-term average: After the dry-out phase, it is assumed that the seasonal variation varies around the long-term average, which relates to the overall average of indoor conditions.

The model proved accurate, with correlation values $R^2 = 0.948 - 0.999$ for the different positions in the CLT. The same model was applied to directly predict the natural frequencies of House Charlie, again based on the previously measured values over three years. Given the high correlation of frequencies with the MC, the model gave similarly high correlations with $R^2 = 0.765 - 0.805$.

This predictive model is of great importance, especially in damage detection through SHM. As a change in the observed natural frequencies may indicate structural change or even damage, it is of utmost importance to determine whether the recorded change can be attributed to natural variations or not.

The seasonal changes in eigenfrequencies are also significant 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 significant.

Paper III

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

Relation to research tasks: Tasks 2, 3, and 4: 2) *develop a dynamic measurement system suitable for AVT and OMA 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 FE 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, categorised as a system type 1 building in this thesis. 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 utilised 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 masses (gravel and screed) were added to the slabs. Additionally, it was concluded that the building's stiffness increased when the façade and non-structural interior walls were installed.

With the large number of AVTs available for calibration of an FE model, an investigation of the influence of different parameters on the dynamic characteristics was performed thereafter. The parameters are typically 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 the model parameters, the eigenmodes and corresponding eigenfrequencies were found to match the experimental ones only roughly. The following parameter variation study emphasised the significance of accurately modelling the CLT material, as in-plane shear stiffness significantly impacted the results. The foundation characteristics and non-structural wall elements were also identified as having a notable effect on the FEA results, which aligns with the conclusions drawn in the appended Paper I for House Charlie.

Finally, a combination of properties was presented that showed good agreement with the measured eigenfrequencies from the AVTs. It is emphasised that numerous parameters influence the results in different ways. A “correct” set of parameters was intentionally not presented as such, as a set cannot be verified uniquely.

Paper III highlight the successful use of the mobile dynamic measurement system developed within the scope of this thesis. The evaluation of the OMA revealed that non-structural elements significantly enhanced the stiffness of the building. In addition, it shows that using commercial software, a standard FE model for design successfully gives natural frequencies and mode shapes comparable to the measured values, given that a careful selection of parameters is made.



Figure 4.1: Photos during testing on the mobile measurement system in 2020 at House Charlie and Linnologen with Carl Larsson, Ebbot Larsson and Osama Abdeljaber

Paper IV

Title: *Dynamic testing and simultaneous model updating of two identical timber buildings with different substructures*

Relation to research tasks: Tasks 3 and 4: 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 FE simulations of the tested buildings, including parametric studies, to investigate and evaluate parameters commonly assumed in a structural design process.*

This study investigates the dynamic behaviour of two nearly identical six-story timber-concrete hybrid buildings in Växjö, Sweden. Both buildings have the same CLT superstructure but differ in their concrete substructures and soil conditions, categorised as system type 1 buildings according to this thesis.

AVTs were performed twice on each building, at different construction stages, before and after the installation of non-structural walls. These tests aimed to capture the buildings' natural frequencies and mode shapes. FE models were developed for each test scenario, resulting in four models in total. These models were parameterised using 14 variables, including moisture content, in-plane shear stiffness of the CLT walls, soil-structure interaction, and uncertain slab loads.

To efficiently update the models and match them with the measured data, the researchers trained four surrogate models using neural networks. These surrogate models significantly reduced computational time and enabled the use of a global optimisation algorithm, Particle Swarm Optimisation (PSO), to fine-tune the parameters. The updated models showed a strong correlation with the measured data, reducing the average error in natural frequency estimation from 23% to 1.8%.

The results revealed that the two buildings exhibited nearly identical dynamic behaviour, despite differences in substructure and soil conditions. This suggests that the timber superstructure is the dominant factor influencing the buildings' dynamic properties. Among all parameters, the in-plane shear stiffness had the most significant impact on the natural frequencies. The study also found that soil-structure interaction had a negligible effect, particularly for the building with a stiffer basement and bedrock foundation. Moisture content and additional slab loads had a limited influence, while non-structural walls mainly affected the first natural frequency.

The study introduced a novel approach by simultaneously updating multiple FE models using surrogate modelling and optimisation. It also provided new insights into the relative importance of various parameters affecting the dynamic behaviour of CLT buildings. The use of surrogate models offers a practical tool for structural designers to perform extensive simulations efficiently.

Paper V

Title: *Multi-Stage Structural Identification of a Tall Timber Building during Construction: The Role of Connections and Non-Structural Elements*

Relation to research tasks: Tasks 3 and 4: 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 FE simulations of the tested buildings, including parametric studies, to investigate and evaluate parameters commonly assumed in a structural design process.*

This study investigates the dynamic behaviour of Fyrtornet, an 11-story, 51-meter-tall timber building in Malmö, Sweden, throughout its construction. The building is categorised as a system type 4 building according to this thesis. It features a structural system in timber, utilising GLT for the frame and CLT for the slabs and walls in the stabilising elevator and staircase shaft. The building rests on a concrete basement and features non-structural elements, including a slanted glass façade, timber façade walls, and internal partition walls.

The research focuses on how connections, non-structural elements, and soil-structure interaction influence the building's stiffness and vibration characteristics. AVTs were conducted at seven different construction stages, to capture changes in the building's natural frequencies and damping ratios. FE models were developed and updated to match the measured modal properties.

Results showed that the natural frequencies decreased as the timber structure was erected, consistent with previous studies. Interestingly, frequencies continued to decline even after the structural frame was completed, suggesting that added mass from non-structural elements had a greater impact than their stiffness contribution. The glass façade, despite its prominent architectural role, contributed minimally to structural stiffness due to its flexible mounting system.

FE models were calibrated using a multi-objective optimisation approach, focusing on parameters such as connection stiffness, foundation stiffness, and the contribution of the glass façade. The empirical equation for slip modulus from Eurocode 5 provided a reasonable approximation for GLT connection stiffness, although it likely underestimates actual stiffness. Model updating revealed that connection stiffness increased during construction, particularly in the final stages when screed and partition walls were installed. This increase was interpreted as a shift toward rigid connection behaviour.

Foundation stiffness evolved from flexible to effectively rigid as construction progressed, likely due to soil consolidation under increasing loads. CLT slab connections showed limited influence due to the building's slenderness, while CLT wall connections exhibited moderate stiffness increases but did not reach rigid behaviour.

The study concludes that non-structural elements, especially screed layers, can significantly affect the global stiffness of timber buildings. It also highlights

the importance of accurately modelling connections and foundation conditions to predict dynamic behaviour.



Figure 4.2: Photo during Ambient Vibration Tests of Fyrtornet in 2023 with Carl Larsson and Osama Abdeljaber.

Paper VI

Title: *Recorded Natural Frequencies of Timber Buildings – A Review*

Relation to research tasks: Task 2 *Perform in-situ measurements to evaluate the performance of buildings with characteristics from the timber-concrete hybrid definition.*

This study reviews the measured natural frequencies of 25 multi-story timber and hybrid timber buildings, ranging in height from 16 to 85 meters. The primary motivation is to assess the accuracy of empirical equations provided by various international building codes for estimating the fundamental natural frequency of buildings, particularly in the context of wind-induced vibration serviceability checks. Timber buildings, due to their lightweight nature, are especially sensitive to such vibrations, making accurate frequency estimation crucial for design.

The authors categorise the buildings into four structural types: light-frame timber (LFT), cross-laminated timber (CLT), glued-laminated timber (GLT), and hybrid timber buildings. CLT buildings are the most represented type in the dataset, while GLT and hybrid buildings tend to reach greater heights. Each building's height, structural system, and first natural frequency are compiled and analysed. The information for the buildings is primarily based on literature research and is complemented by measurements by the authors on additional buildings.

The study evaluates empirical equations from five building codes: the Eurocode (EC), the American Society of Civil Engineers (ASCE), the Canadian National Building Code (NBCC), the Japanese Architectural Institute (AIJ), and the Italian National Technical Code (NTC). These equations typically relate the building's height to its natural frequency, but none are tailored explicitly for timber structures. The analysis reveals that most of these equations, especially those from ASCE and NTC, tend to underestimate the natural frequencies of timber buildings. The Japanese AIJ and Eurocode equations perform better, particularly those assuming an inverse proportionality between frequency and height.

To improve accuracy, the authors propose a new empirical equation specifically for timber and hybrid timber buildings: $f = 60/h$, where f is the fundamental natural frequency in Hz and h is the building height in meters. This equation achieves a high coefficient of determination, indicating a strong fit with the dataset. Most buildings fall within a $\pm 20\%$ range of this estimate, although some outliers are explained by unique structural features such as heavy concrete slabs, massive concrete cores, or irregular shapes.

The study concludes that while existing building codes provide rough estimates, they lack precision for timber structures. The proposed equation offers a more reliable alternative for preliminary design and serviceability checks. However, the authors caution that buildings with unusual mass or stiffness distributions may deviate significantly from the estimate. They recommend that future research refine

the prediction model by incorporating additional parameters, such as structural system type, slenderness, and material composition.

5 Conclusions & Future Work

5.1 Conclusions

This thesis has investigated the dynamic behaviour of timber-concrete hybrid buildings through a combination of in-situ measurements, FE modelling, and model updating techniques.

The initial interview study in the appended Paper I revealed a fragmented design landscape for timber-concrete hybrid buildings in Sweden. A key finding was the inconsistent use of static models and computational tools among structural designers, even within the same project. This lack of standardisation contributes to model uncertainty and complicates collaborative workflows.

The categorisation of four structural system types provided a framework for understanding the diversity of timber-concrete hybrid structures. This typology not only informed the selection of case buildings in further studies but also highlighted the need for improved knowledge transfer and design integration across disciplines.

The long-term monitoring of House Charlie (Paper II) revealed a strong correlation between seasonal moisture content variations and changes in natural frequencies. This first-of-its-kind finding for timber-concrete hybrids underscores the importance of environmental factors in dynamic analysis, model updating and SHM. Others, such as Aloisio et al. (2025), have also followed up on this study, highlighting the importance of environmental factors.

A major contribution of this thesis was the development of a mobile, battery-powered data acquisition system for Ambient Vibration Testing (AVT). As detailed in the appended Papers II-VI, the system was successfully deployed on active construction sites and finalised buildings.

The system's modularity, synchronisation accuracy, and ease of deployment enabled repeated measurements during construction phases, an approach rarely documented in the literature. The system directly addresses these critical requirements for in-situ validation of design assumptions, opening new possibilities for real-time structural monitoring and overcoming the limitations of traditional cabled systems.

Meanwhile, the construction-phase evaluations of House Biologen (Paper III) and the Skymningen buildings (Paper IV) highlighted the evolving stiffness contributions of non-structural elements and the critical role of in-plane shear

stiffness in CLT walls. Paper V, covering the much taller Fyrtornet, further emphasised the dynamic influence of connections and foundation stiffness in tall buildings.

By validating FE models against in-situ measurements, this thesis provides a pathway to reduce model uncertainty. The novel use of surrogate models trained by neural networks (Paper IV) further demonstrates how computational efficiency can be improved without sacrificing accuracy, enabling more robust design workflows.

The results of this research have several implications for structural designers working with timber-concrete hybrid buildings:

- **In-plane shear stiffness of CLT walls** emerged as the most influential parameter in modelling timber-concrete hybrids using CLT shear walls. The reduction factor k_{88} , used to account for lamella glueing, must be carefully calibrated. The findings suggest that current design guidelines may overestimate stiffness, especially when acoustic insulation is present at slab-wall connections.
- **Soil-structure interaction** proved to be sufficient using Winkler spring models for the buildings studied, and their influence varied depending on substructure stiffness and soil conditions. In the Skymningen buildings (Paper IV), soil-structure interaction had minimal impact, whereas in Fyrtornet (Paper V), foundation stiffness evolved significantly during construction.
- **Timber connections** have shown limited influence. The empirical equation for slip modulus k_{ser} from EC5 provides a practical method for estimating connection stiffness for Fyrtornet (Paper V).
- **Moisture content** affects both material properties and dynamic behaviour. Seasonal variations in MC should be considered, especially when using it for SHM and damage detection, although their importance in structural design is limited.

Timber-concrete hybrid buildings represent a promising solution for sustainable construction, capable of meeting both structural and environmental performance criteria. This thesis has shown that with appropriate modelling, measurement, and collaboration, the dynamic behaviour of such buildings can be accurately predicted and managed. The integration of in-situ data with FE modelling not only enhances design reliability but also opens new paths for intelligent monitoring and adaptive design.

5.2 Future work

The research presented in this thesis has significantly advanced the understanding of the dynamic behaviour of timber-concrete hybrid buildings through in-situ

measurements, FE modelling, and model updating. However, several areas remain open for further investigation and development:

1. **Structural Design Data Sharing** is identified in this thesis as an area with limited tools or regulations, especially compared to other fields of information workflow (such as architectural and MEP) within the design of buildings.
2. **Extended Long-Term Monitoring.** While the long-term monitoring of House Charlie provided valuable insights into seasonal variations and moisture content effects, additional long-term studies on other building types and climates are needed. These should include continuous monitoring of both environmental parameters and structural responses to understand time-dependent behaviours and degradation mechanisms better.
3. **Incorporation of Forced Vibration Testing.** The current work relies on AVT and operational modal analysis. Future studies should incorporate forced vibration tests to obtain scaled mode shapes and frequency response functions, which would enhance the accuracy of model updating and allow for more detailed validation of FE models.
4. **Influence of Non-Structural Elements.** The contribution of non-structural walls was shown to be influential. Future work should focus on developing standardised modelling techniques for these elements and quantifying their influence across different building configurations and materials.

To support the second point, a new long-term monitoring system has been installed at House Fyrtornet as part of the thesis. This system will enable continuous data collection on accelerations, enabling OMA to give natural frequencies and damping values. In addition, the indoor climate and the timber MC are monitored over time. While no evaluation is done in the thesis, future work on Fyrtornet will focus on analysing this data to validate predictive models, assess long-term trends, and explore the impact of environmental factors on taller hybrid structures.

References

- Abrahamsen, R. (2017). Mjøstårnet-construction of an 81 m tall timber building. *Internationales Holzbau-Forum IHF*, pages 1–12.
- Abrahamsen, R., Bjertnæs, M. A., Bouillot, J., Brank, B., Cabaton, L., Crocetti, R., Flamand, O., Garains, F., Gavric, I., Germain, O., Hahusseau, L., Hameury, S., Johansson, M., Johansson, T., Ao, W. K., Kurent, B., Landel, P., Linderholt, A., Malo, K., Manthey, M., Nàvik, P., Pavic, A., Perez, F., Rönquist, A., Stamatopoulos, H., Sustersic, I., and Tulebekova, S. (2020). Dynamic response of tall timber buildings under service load - The Dynattb research program. *Proceedings of the International Conference on Structural Dynamic , EUROODYN*, 2:4900–4910.
- Aloisio, A., Pasca, D., Tomasi, R., and Fragiaco, M. (2020). Dynamic identification and model updating of an eight-storey CLT building. *Engineering Structures*, 213:110593.
- Aloisio, A., Pasca, D. P., Kurent, B., and Tomasi, R. (2025). Long-term continuous dynamic monitoring of an eight-story CLT building. *Mechanical Systems and Signal Processing*, 224(July 2024):112094.
- Amaddeo, C., Dorn, M., and Martinelli, L. (2024). Initial monitoring of a six-story lightweight timber frame building under different environmental conditions. *Journal of Civil Structural Health Monitoring*.
- Austrian Standards Institute (2014). Eurocode 5: Bemessung und Konstruktion von Holzbauten Teil 1-1: Allgemeines — Allgemeine Regeln und Regeln für den Hochbau. Nationale Festlegungen zur ÖNORM EN 1995-1-1 und nationale Erläuterungen [Eurocode 5 – Design of timber structures – Part 1-1: General – Common rules and rules for buildings – National specifications concerning ÖNORM EN 1995-1-1 and national comments].
- Bartlett, A. I., Hadden, R. M., and Bisby, L. A. (2019). A review of factors affecting the burning behaviour of wood for application to tall timber construction.
- Bishop, C. M. and Nasrabadi, N. M. (2006). *Pattern recognition and machine learning*, volume 4. Springer.
- Bodig, J. and Jayne, B. A. (1982). *Mechanics of Wood and Wood Composites*. Van Nostrand Reinhold Publishing.
- Brincker, R. (2015). *Introduction to Operational Modal Analysis*. Wiley, 1st edition.
- Council on Tall Buildings and Urban Habitat (2022). The State of Tall Timber: A Global Audit. Available at <https://www.ctbuh.org/mass-timber-data/>.

- Digilent (2025). Webdaq 504.
- Dorn, M., Abdeljaber, O., and Klaeson, J. (2019). Structural Health Monitoring of House Charlie. Project Report. Linnaeus University Press.
- Edskär, I. and Lidelöv, H. (2017). Wind-induced vibrations in timber buildings-parameter study of cross-laminated timber residential structures. *Structural Engineering International*, 27:205–216.
- Elliott, K. S. (2013). *Multi-storey precast concrete framed structures*. Wiley-Blackwell, second edition.
- European committee for standardization (2002). Eurocode: Basis of structural design.
- European committee for standardization (2011). Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings.
- European committee for standardization (2016a). En 338 - structural timber - strength classes. Technical report.
- European committee for standardization (2016b). EN 384 - Structural timber - Determination of characteristic values of mechanical properties and density.
- European committee for standardization (2021). EN 16351 - Timber structures - Cross laminated timber - Requirements.
- Flamand, O., Giovannelli, G., and Manthey, M. (2023). Data processing to assess structural damping of tall timber buildings. In *EVACES*.
- Forrester, A., Sobester, A., and Keane, A. (2008). *Engineering design via surrogate modelling: a practical guide*. John Wiley & Sons.
- Fossilfritt Sverige (2018). En klimatneutral värdekedja i bygg- och anläggningssektorn 2045. En färdplan för fossilfri konkurrenskraft [A climate-neutral chain in the construction sector year 2045. A roadmap for fossil-free competitiveness]. Available at https://fossilfritt Sverige.se/wp-content/uploads/2020/10/ffs_bygg_anlaggningssektorn.pdf.
- Fröderberg, M. (2014). The human factor in structural engineering: A source of uncertainty and reduced structural safety. Licentiate Thesis.
- Gustafsson, A., Crocetti, R., Just, A., Landel, P., Olsson, J., Pousette, A., Silfverhielm, M., and Östman, B. (2019). *The CLT Handbook*. Skogsindustrierna.
- Halab-Kessira, L. and Ricard, A. (1999). Use of the trial and error method for the optimization of the graft copolymerization of a cationic monomer onto cellulose. *European Polymer Journal*, 35(6):1065–1071.
- Hu, L. and Auclair, S. C. (2018). Advanced wood-based solutions for mid-rise and high-rise construction: In-situ testing of the origine 13-storey building for vibration and acoustic performances. Technical report, FP Innovations.
- JCSS Joint Committee on Structural Safety (2001). Probabilistic model code. Technical report.
- Johansson, M., Linderholt, A., Jarnerö, K., and Landel, P. (2016). Tall timber buildings: A preliminary study of wind-induced vibrations of a 22-storey building. In *World Conference on Timber Engineering (WCTE 2016), August 22-25*,

- 2016, Vienna, Austria. Vienna University of Technology.
- Kamali, A. (2021). Dynamic soil-structure interaction analysis of railway bridges. Technical report, Doctoral Thesis in Structural Engineering and Bridges Dynamic.
- Karacabeyli, E. and Brad, D. (2013). *CLT Handbook*. FPInnovations.
- Kurent, B., Ao, W. K., Pavic, A., Pérez, F., and Brank, B. (2023). Modal testing and finite element model updating of full-scale hybrid timber-concrete building. *Engineering Structures*, 289.
- Kurent, B., Brank, B., and Ao, W. K. (2021). Model updating of seven-storey cross-laminated timber building designed on frequency-response-functions-based modal testing. *Structure and Infrastructure Engineering*, 0:1–19.
- Kurent, B., Friedman, N., Aloisio, A., Pasca, D., Tomasi, R., and Brank, B. (2024a). Bayesian model updating of eight-storey clt building using modal data. *Probabilistic Engineering Mechanics*, 77:103642.
- Kurent, B., Friedman, N., and Brank, B. (2024b). Modelling of Multi-Storey Cross-Laminated Timber Buildings for Vibration Serviceability. *Buildings*, 14:689.
- Landel, P. (2022). Wind-induced vibrations in tall timber buildings. Licentiate Thesis. Linnaeus University Press.
- Landel, P. and Linderholt, A. (2022). Reduced and test-data correlated fe-models of a large timber truss with dowel-type connections aimed for dynamic analyses at serviceability level. *Engineering Structures*, 260:114208.
- Leishman, T., Ventura, C., Motamedi, M., Cassidy, J. F., and Dosso, S. E. (2024). Ambient vibration testing of canada’s tallest wood frame building. In *Lecture Notes in Civil Engineering*, volume 514 LNCE, pages 704–711. Springer Science and Business Media Deutschland GmbH.
- Linderholt, A., Landel, P., and Johansson, M. (2024). Forced response measurements on a seven-story timber building. *Conference Proceedings of the Society for Experimental Mechanics Series*, pages 1–4.
- Lindström, M. and Lagerqvist, O. (2015). Eurokoderna och eks-effekter på byggekostnader. Technical report, SBUF.
- Malaspina, M., Powell, D., Verhaegh, R., Dennis, J., and Tomek, P. (2023). Dynamic performance of hybrid timber-concrete high-rise under wind induced excitation measured through on-site testing. In *SECED 2023 Conference*.
- Malmqvist, T., Erlandsson, M., Francart, N., and Kellner, J. (2018). Minskad klimatpåverkan från flerbostadshus [Reduced climate impact from residential buildings]. SBUF Report 13355.
- Manthey, M., Flamand, O., Jalil, A., Pavic, A., and Ao, W. K. (2021). Effect of non-structural components on natural frequency and damping of tall timber building under wind loading. In *World Conference on Timber Engineering 2021, WCTE 2021*.
- Melchers, R. E. and Beck, A. T. (2018). *Structural reliability analysis and prediction*. John Wiley & sons.

- Mindlin, R. (1951). Influence of rotatory inertia and shear on flexural motions of isotropic, elastic plates. *ASME Journal of Applied Mechanics*, 18:31–38.
- Mohammadyzadeh, S. and Zhou, J. (2025a). Modal characteristics of two mid-rise mass timber-steel hybrid buildings utilizing ambient vibration tests. In *World Conference on Timber Engineering*, pages 2481–2487.
- Mohammadyzadeh, S. and Zhou, J. (2025b). A survey on the dynamic properties of mid- and high-rise mass timber buildings. pages 3302–3308. *World Conference on Timber Engineering*.
- Mugabo, I., Barbosa, A. R., and Riggio, M. (2019). Dynamic characterization and vibration analysis of a four-story mass timber building. *Frontiers in Built Environment*, 5.
- Muszynski, L., Hansen, E., Fernando, S., Schwarzmann, G., and Rainer, J. (2017). Insights into the global cross-laminated timber industry. *Bioproducts business*, 2:77–92.
- Muszyński, L., Larasatie, P., Guerrero, J. E., and Albee, R. (2020). Global CLT industry in 2020: Growth beyond the Alpine Region Teak Furniture Industry View project Digitalization in the Forest Sector Business View project. *Proceedings of the 63rd International Convention of Society of Wood Science and Technology*.
- Olsen, M. F. and Hansen, O. (2016). *Measuring Vibrations and assessing Dynamic Properties of tall Timber Buildings*. PhD thesis, NTNU.
- Pettersson, J. and Edström, T. (2024). *An Evaluation of the Dynamic Behavior from Ambient Vibrations in a Timber High-Rise Building A Comparison Between Experimental In-Situ Tests and Numerical Optimization*. PhD thesis, KTH.
- Reynolds, T., Casagrande, D., and Tomasi, R. (2016). Comparison of multi-storey cross-laminated timber and timber frame buildings by in situ modal analysis. *Construction and Building Materials*, 102:1009–1017.
- Reynolds, T., Åsa Bolmsvik, Vessby, J., Chang, W.-S., Harris, R., Jonathan, B., and Bregulla, J. (2014). Ambient vibration testing and modal analysis of multi-storey cross-laminated timber buildings. *World Conference on Timber Engineering, WCTE14*.
- Samadian, D., Muhit, I. B., and Dawood, N. (2024). Application of data-driven surrogate models in structural engineering: a literature review. *Archives of Computational Methods in Engineering*, pages 1–50.
- Schickhofer, G. (1994). *Starrer und nachgiebiger Verbund bei geschichteten, flächenhaften Holzstrukturen*. Dissertation. Technischen Universität Graz, Fakultät für Bauingenieurwesen der Technischen Universität Graz.
- Skellefteå Kommun (2021). Sara Kulturhus, FAQ Konstruktion och Teknik. Available at: <https://www.sarakulturhus.se/sv/vanliga-fragor/faq-konstruktion-och-teknik/>.
- Stoner, M. and Pang, W. (2020). Simulated Performance of Cross-Laminated Timber Residential Structures Subject to Tornadoes. *Frontiers in Built Environment*, 6.

- Tulebekova, S., Malo, K. A., and Rønnquist, A. (2023). Dynamic identification and model calibration of connection stiffness in multi-storey cross-laminated timber buildings. *Journal of Building Engineering*, 72.
- Tulebekova, S., Malo, K. A., Rønnquist, A., and Nåvik, P. (2022). Modeling stiffness of connections and non-structural elements for dynamic response of taller glulam timber frame buildings. *Engineering Structures*, 261:114209.
- United Nations (2024). Global Status Report for Buildings and Constructions.
- Wallner-Novak, M., Koppelhuber, J., and Pock, K. (2014). *Cross-Laminated Timber Structural Design, Basic design and engineering principles according to Eurocode*. proHolz Austria.
- Wang, J. Y., Stirling, R., Fpinnovations, P. I. M., Taylor, A., Lloyd, J., Kirker, G., Lebow, S., and Mankowski, M. E. (2018). Durability of mass timber structures: A review of the biological risks. Technical report.
- Younis, A. and Dadoo, A. (2022). Cross-laminated timber for building construction: A life-cycle-assessment overview. *Journal of Building Engineering*, 52:104482.