Graduation Plan

Master of Science Architecture, Urbanism & Building Sciences

Graduation Plan: All tracks

Submit your Graduation Plan to the Board of Examiners (Examencommissie-BK@tudelft.nl), Mentors and Delegate of the Board of Examiners one week before P2 at the latest.

The graduation plan consists of at least the following data/segments:

Personal information	
Name	Annebel van der Meulen
Student number	6031579

Studio		
Name / Theme	Building Technology Graduation Studio	
Main mentor	Simona Bianchi	Structural engineering, hazard analysis, seismic analysis
Second mentor	Michela Turrin	Computational design, design informatics
Argumentation of choice of the studio	Not applicable	

Graduation project	
Title of the graduation project	Dynamic Timber: A Seismic Analysis Workflow for Tall Timber Structures with Variable Mass and Stiffness
Goal	
Location:	Europe (Eurocodes, case study location to be determined)
The posed problem,	Current practice-oriented seismic analysis methods for tall timber structures are not well integrated into the main design process and do not consider variable stiffness and mass over the structure's lifetime.
research questions and	**Main Research Question** How can a practice-oriented computational workflow for the seismic analysis of tall timber structures be integrated into the main design workflow and utilize variable stiffness and mass parameters? **Sub-Questions** 1. What are the trends in tall timber construction? 2. What are the existing (practice-oriented) methods for designing tall timber structures under seismic loads and what are their limitations? 3. Which variable phenomena impact the stiffness and mass of the tall timber structure and how can they be quantified? 4. How can a practice-oriented seismic model utilize component-level experimental data?

	5. What is the impact of the variable phenomena on the seismic behavior of the tall timber structure? 6. How does this modelling strategy and its results compare to that of previous researchers? 7. How does this computational workflow impact the analysis process and decision making of the engineer?
design assignment in which these result.	This present research will develop a computational workflow for the seismic analysis of tall timber structures which: 1. Integrates the seismic analysis model seamlessly into the main design workflow 2. Simplifies the process for setting the parameters in a component-level model for seismic analysis 3. Includes a lifetime analysis option which considers the variables which impact the stiffness and mass of the structure 4. Provides the engineer with component-level data over time This will be achieved by: 1. Creating a script which automatically converts input geometry and identity data into the seismic analysis model within the same environment 2. Providing a database of current experimental strength values for mass timber and its structural connections, and a user input space for building standard analysis parameters 3. Operationalizing the stiffness and mass value input over time in relation to changing time or event input parameters (moisture, fire, seismic, etc.) 4. Outputting stiffness, deflection, and load data of the various components of the mass timber structure over time, highlighting critical retrofitting areas and moments

Research Questions and Research Methodology

Main Research Question
How can a practice-oriented computational workflow for the seismic analysis of tall timber structures be integrated into the main design workflow and utilize variable stiffness and mass parameters?

Problem Investigation
via literature review

What are the trends in tall timber construction?

What are the existing (practice-oriented) methods for designing tall timber structures under seismic loads and what are their limitations?

Which variable phenomena impact the stiffness and mass of the tall timber structure and how can they be quantified?

Solution Design
via computational design

How can a practice-oriented seismic model utilize component-level experimental data?

What is the impact of the variable phenomena on the seismic behavior of the tall timber structure?

Design Validation
via comparative analysis

How does this modelling strategy and its results compare to that of previous researchers?

Implementation
via case study

How does this computational workflow impact the analysis process and decision making of the engineer?

Literature Review
This methodology will be used throughout to support the other methodologies being used, answering the following questions:

- What component-level data is available and appropriate for this computational workflow?

- What time-based data is available for stiffness variables?

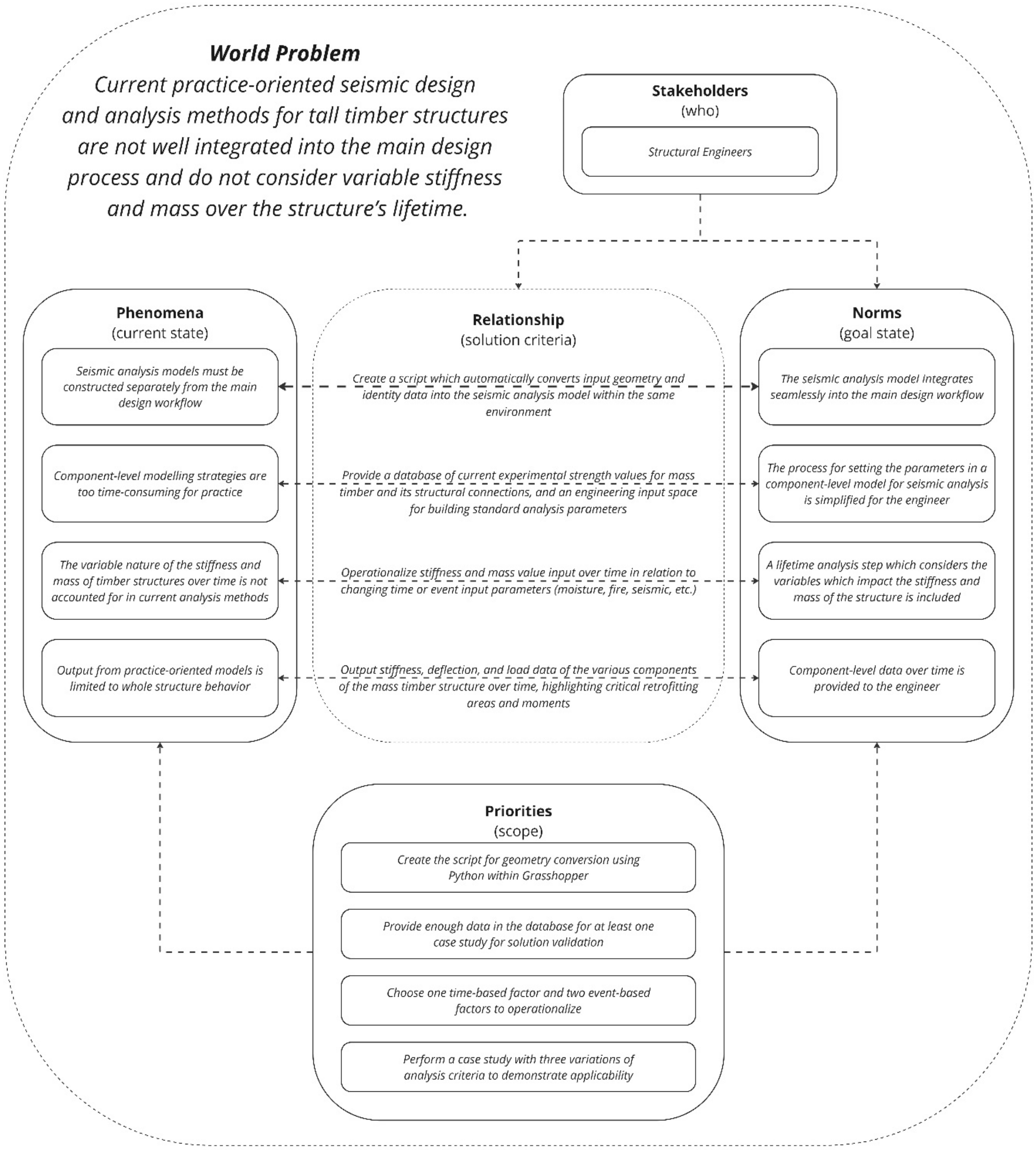
- How does the building standard prescribe the seismic design of tall timber structures?

- What standard factors are appropriate to use for this computational workflow?

- How is a proper comparative analysis between computational models conducted?

- What kind of case study will be useful (ie. new structure or existing structure)?

- What existing structure has enough data to be used as a case study?


World Problem
Current practice-oriented seismic design and analysis methods for tall timber structures are not well integrated into the main design process and do not consider variable stiffness and mass over the structure's lifetime.
Stakeholders
(who)
Structural Engineers
Phenomena
(current state)
Seismic analysis models must be constructed separately from the main design workflow
Component-level modelling strategies are too time-consuming for practice
The variable nature of the stiffness and mass of timber structures over time is not accounted for in current analysis methods
Output from practice-oriented models is limited to whole structure behavior
Relationship
(solution criteria)
Create a script which automatically converts input geometry and identity data into the seismic analysis model within the same environment
Provide a database of current experimental strength values for mass timber and its structural connections, and an engineering input space for building standard analysis parameters
Operationalize stiffness and mass value input over time in relation to changing time or event input parameters (moisture, fire, seismic, etc.)
Output stiffness, deflection, and load data of the various components of the mass timber structure over time, highlighting critical retrofitting areas and moments
Norms
(goal state)
The seismic analysis model integrates seamlessly into the main design workflow
The process for setting the parameters in a component-level model for seismic analysis is simplified for the engineer
A lifetime analysis step which considers the variables which impact the stiffness and mass of the structure is included
Component-level data over time is provided to the engineer
Priorities
(scope)
Create the script for geometry conversion using Python within Grasshopper
Provide enough data in the database for at least one case study for solution validation
Choose one time-based factor and two event-based factors to operationalize
Perform a case study with three variations of analysis criteria to demonstrate applicability

Process

Method description

The above research questions will be answered with four different research methods: a literature review, computational design, comparative analysis, and a case study.

Literature Review

Problem investigation was completed via a literature review, utilizing a snowballing method. It began by reviewing other current wholistic literature studies for trends in tall timber construction around the world and the current research areas. These papers included a wholistic review of tall timber structures (Gonzalez et al. 2022), a literature review to determine main design considerations in tall timber structures (Ilgin 2023), and a review of the seismic behavior of tall cross-laminated timber structures (Izzi et al. 2018). This provided a good overview of what the field currently looks like, providing the research with key terms and a narrowing of the scope. It also provided a list of credible resources to begin diving deeper into specific areas of research.

Through this initial literature review, the trends, existing practice-oriented seismic modelling methods, and phenomena which impact the stiffness and mass of tall timber structures were identified. This helped to inform the scope and goals of the project. It's important to note that while this initial literature review is complete, more studies will need to be identified and referenced while completing the following stages of the research. However, further literature review will be focused on collecting experimental data and identifying factors to be used for the seismic analysis, rather than informing the scope and goals of the project.

Computational Design

Computational design methods will be used to develop the computational workflow for a practice-oriented model for the seismic analysis of tall timber structures. The workflow will be separated into three steps, the first which provides simplified user input for the engineers, the second which analyzes the initial state of the structure, and the third which allows the engineer to run lifetime analyses on the structure for variable stiffnesses and masses. The focus of the computational design is creating a script which utilizes component-level experimental data to build the seismic analysis model and utilizes a time step to check variable stiffnesses and masses. Through this research method, the goal is to answer the question of how this can be done, and what the impact of the lifetime analysis is.

Comparative Analysis

A comparative analysis will be conducted to test the accuracy of the seismic analysis model. This will be completed with a direct comparison to the results of the modelling strategy which this is being based on (Rinaldi et al. 2021). This will inform the calibration of the meshes in the finite element model.

Case Study

A case study will be modelled with this computational workflow to demonstrate its capabilities. If an existing structure is utilized as the case study model, then the results of the lifetime analysis of the structure could be compared to the current state of the structure. It will have to be investigated whether an appropriate structure exists for such a comparison, while still demonstrating the other aspects of the tool.

Literature and general practical references

The Eurocodes will be used to guide the analysis process, particularly the current drafts for Eurocodes 5 and 8, as these include mass timber material design:

CEN. Eurocode 5: Design of timber structures - Part 1-1: General – Common rules and rules for buildings. Brussels: Comite´ Europe´en de Normalisation; 2005.
CEN/TC250. prEN 1995-1-1:2023: Eurocode 5: Design of timber structures - Part 1-1: General – Common rules and rules for buildings. Draft document 12-04-2023. Brussels: Comite´ Europe´en de Normalisation; 2023.
CEN. Eurocode 8: design of timber structure - Part 1: General rules, seismic actions and rules for buildings. Brussels: Comite´ Europe´en de Normalisation; 2005.
CEN/TC250. prEN 1998-1-1:2022: Eurocode 8: design of timber structure - Part 1: General rules, seismic actions and rules for buildings. Draft document 22-11-2022. Brussels: Comite´ Europe´en de Normalisation; 2022.

The computational modelling method for finite analysis of tall timber buildings put forth by Rinaldi et al. and Christovasilis et al. will be the main reference for developing the model for analysis:

Rinaldi, Vincenzo, Daniele Casagrande, Catia Cimini, Maurizio Follesa, and Massimo Fragiacomo. "An Upgrade of Existing Practice-Oriented FE Design Models for the Seismic Analysis of CLT Buildings." _Soil Dynamics and Earthquake Engineering_ 149 (October 1, 2021): 106802. https://doi.org/10.1016/j.soildyn.2021.106802.
Christovasilis, I. P., L. Riparbelli, G. Rinaldin, and G. Tamagnone. "Methods for Practice-Oriented Linear Analysis in Seismic Design of Cross Laminated Timber Buildings." _Soil Dynamics and Earthquake Engineering_ 128 (January 1, 2020): 105869. https://doi.org/10.1016/j.soildyn.2019.105869.

The CLT timber properties and connections properties will be obtained from various experimental tests, including:

Bogensperger, Thomas, Thomas Moosbrugger, and Gregor Silly. "Verification of CLT-Plates under Loads in Plane," June 2, 2016.
Blass, H., and Peter Fellmoser. "Design of Solid Wood Panels with Cross Layers," 2004. https://www.semanticscholar.org/paper/Design-of-solid-wood-panels-with-cross-layers-Blass-Fellmoser/0ac31e3f0a8923666100baa6e19f6a87c91f7a1a.
Flaig, M, and H J Blaß. "Shear Strength and Shear Stiffness of CLT-Beams Loaded in Plane," 2013.
Gavric, Igor, Massimo Fragiacomo, and Ario Ceccotti. "Cyclic Behaviour of Typical Metal Connectors for Cross-Laminated (CLT) Structures." _Materials and Structures_ 48, no. 6 (June 2015): 1841–57. https://doi.org/10.1617/s11527-014-0278-7.
Gavric, Igor, Massimo Fragiacomo, and Ario Ceccotti. "Cyclic Behavior of Typical Screwed Connections for Cross-Laminated (CLT) Structures." _European Journal of Wood and Wood Products_ 73, no. 2 (March 2015): 179–91. https://doi.org/10.1007/s00107-014-0877-6.
Gavric, Igor, Massimo Fragiacomo, and Ario Ceccotti. "Cyclic Behavior of CLT Wall Systems: Experimental Tests and Analytical Prediction Models." _Journal of Structural Engineering_ 141, no. 11 (November 2015): 04015034. https://doi.org/10.1061/(ASCE)ST.1943-541X.0001246.

The comparative study will be influenced by the validation processes demonstrated in Pozza et al. and in Rinaldi et al. (previously cited), comparing either to the results of Gavric et al. (previously cited) or that of the SOFIE project:

Pozza, Luca, Marco Savoia, Luca Franco, Anna Saetta, and Diego Talledo. "Effect Of Different Modelling Approaches On The Prediction Of The Seismic Response Of Multi-Storey CLT Buildings," 2017. https://www.witpress.com/elibrary/cmem-volumes/5/6/1930.

Ceccotti, Ario, Carmen Sandhaas, Minoru Okabe, Motoi Yasumura, Chikahiro Minowa, and Naohito Kawai. "SOFIE Project – 3D Shaking Table Test on a Seven-Storey Full-Scale Cross-Laminated Timber Building." _Earthquake Engineering & Structural Dynamics_ 42, no. 13 (2013): 2003–21. https://doi.org/10.1002/eqe.2309.

The variable parameters which impact mass and stiffness will be collected from previous research on each topic. The possible topics include moisture, biological deterioration, fire event, previous seismic event, or scheduled renovation/retrofit. Thus far, the references investigated include:

Schmidt, Evan, and Mariapaola Riggio. "Monitoring Moisture Performance of Cross-Laminated Timber Building Elements during Construction." _Buildings_ 9, no. 6 (June 2019): 144. https://doi.org/10.3390/buildings9060144.

The case study will either be a new developed building in a location, or model an existing tall timber structure, such as Mjøstårnet. If so, a reference for the construction of this structure must be found.

Solution Design

Defining the Scope

Software Environment

Most of the existing software for finite element modelling is separated from the main design workflow and requires the structural engineer to reconstruct the model in this other environment. Some plug-ins or add-ons for Rhino and Grasshopper or REVIT exist, but they do not automatically generate analysis models from Rhino or Grasshopper geometry. Furthermore, the output is limited to what the plug-in is designed to output, and the structure of it remains unclear. One advantage of the FEM-Design API for Grasshopper is that it is open-source and thus can be referenced when creating the computational workflow for this project.

The computational workflow will be developed within the Grasshopper environment for Rhino 8, utilizing Python in Grasshopper (GHpython). This will provide control over the format of the building model input for automatic analysis model generation, and control over the output structure for lifetime analysis of changing stiffness and mass. Existing finite element modelling plug-ins for Grasshopper may be referenced to determine possible solution algorithms to use for solving the finite element equation produced by the GHpython script, but a better understanding of these is still needed.

Construction Type

To ensure that the workflow is designed such that it is applicable for the majority of tall timber construction types, the model will be designed for the primary trends in tall timber structure as listed below:

Table __ – Construction Type Scope

Height	8 stories tall
Form	Rectilinear
Function	Residential
Core	Centered
Materials	CLT panels and glulam beams, concrete core and podium
Structural System	Shear-frame system
Building Standard	Eurocode (drafts and supporting research)

The height of tall timber structures is defined as over 8 stories tall (above the podium). For simplicity's sake, only rectilinear forms will be considered with walls in only two perpendicular directions. The function of the building will be residential, which will matter when considering renovation designs and frequencies. The core will remain centralized, avoiding complicated eccentric forces and torsional forces. The materials database will be focused on CLT and glulam members and their connection between themselves as well as to concrete. The core and podium will be made of concrete and will be assumed as relatively rigid elements. The structural system considered will be the shear-frame system as this is the most common and seems to have the most structural benefits when properly implemented. Finally, though the current Eurocode does not have proper procedures and factors for the seismic analysis of tall CLT structures, it will be used as a basis and supporting drafts and research will be referenced to fill the knowledge gaps of the standard. As much as is possible, the computational workflow will be designed in such as way that it can be adjusted for the less prominent tall timber construction types.

Component Database

Current computational modelling strategies rely on experimental data for the stiffnesses and strengths of timber materials and connection hardware. As will be explained later, a semi-component level modelling strategy will be used, so the mechanical properties of the timber material and connection hardware must be collected from current research. It will be organized in a database such that the engineer can select the hardware and timber material being used, and the appropriate experimental values will be utilized.

The strengths database shall be designed to be expandable so that as research continues more data can be included into the database. Without providing a database, engineers would need to seek out existing sources themselves to utilize in the component model. This could cause inaccuracies in the analysis if the type of data that is used is not appropriate for the component-level modelling approach that the finite element analysis will be designed around. Clear instructions for the accumulation of data within this database will be provided, to minimize inaccuracies in the analysis results.

An important limitation to note of this approach is that the component level experimental tests are conducted on isolated components, meaning that the second-order effects (such as friction or overstrength) that impact the component's behavior in-situ will not be accounted for. A factor must be incorporated into the database to account for this; it will be arbitrarily assigned for now such that once future research determines this factor it can be implemented.

Seismic Analysis Parameters Input

The seismic analysis parameters input shall be kept separate from the main analysis script so that future implementations of this computational workflow can be adjusted for different construction standards. For the purposes of this research, the seismic analysis parameters will follow the Eurocodes, as more than half of current tall timber structures are in Europe. This will also achieve the learning goal of the present researcher to become more familiar with the Eurocodes.

These parameters include:

- Design acceleration spectrum (Sda)
- Behavior factor (q)
- Load factors for combinations

Parameters Impacting Stiffness and Mass

One time-based parameter and two event-based parameters will be integrated into the project. As an existing model for the prediction of mold growth has been identified, and given that it is closely linked to moisture, the time-based parameter that will be considered is biological deterioration. The first event-based parameter to be considered will be a low-force seismic event. This type of seismic event should cause some damage but not enough to render the building unsafe. An analysis of the structure without renovations after a small seismic event is within reason and should be relatively quick to implement as the results can be derived from the model itself. The second event-based parameter to be included in the scope of this project will be renovations and retrofit. This is because of the simplicity of the impact on the stiffness and mass of the structure, the complexity will lie in identifying the moments in time where this occurs. Fire events were not chosen to be included within the scope of this project because of the complicated fire modelling process it would require and the limited knowledge of how fire spreads through a tall CLT structure.

Computational Workflow

The computational workflow will have three main input zones: the geometry and wall construction data, the component database constructed from reviews of previous research, and the seismic analysis parameters and deflection limits obtained from the building standard. The seismic analysis model will be automatically generated with a Grasshopper script, following the referenced modelling strategy (Rinaldi et al. 2021). A two-step analysis will occur, first with an iterative process to determine the initial design of the structure, then with a service life analysis with time steps and changing stiffness or mass parameters. Finally, the output will provide the engineer with initial and service life data of each wall and its connections. It will pinpoint moments in time where renovations or retrofit will be required to effectively extend the life of the building.

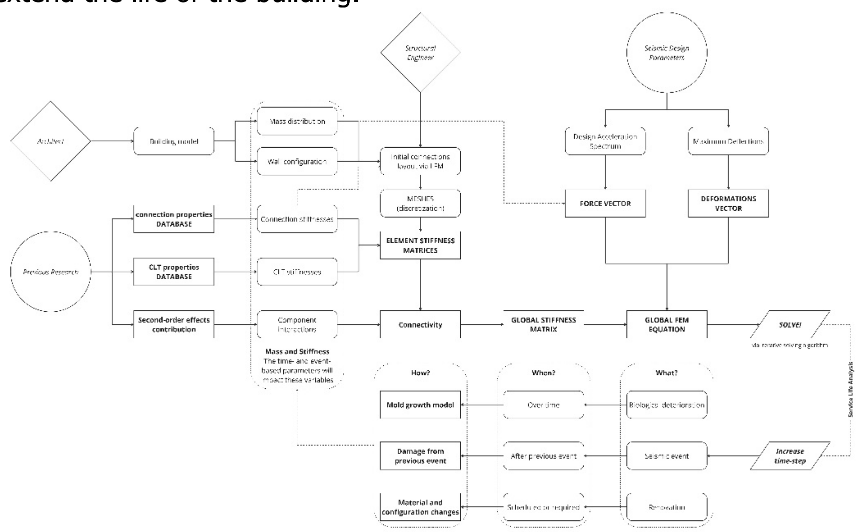


Figure __ – Full computational workflow

Input Parameters

The building model will be supplied by the architect such that it is rotated inline with the existing cartesian grid in the Rhino space, with one corner of the bounding box of the structure at the origin. The walls and floors shall be modelled as enclosed volumes, with holes for windows and stairwells included. Structural walls should be clearly distinguished from non-structural walls via _______________. Structural walls will be indexed from left to right (for wall in the y-direction), then top to bottom (for walls in the x-direction). The grasshopper script will convert these to two-dimensional surfaces centered within the thickness of the wall or floor. Floor thickness should be respected by the wall heights, as the floor between walls is an integral part of the modelling strategy.

The structural engineer will provide an initial connections layout, indexed to match the index order of the walls as produced by the script. The engineer can indicate the connection type by referring to or adding to the database. The components database will be an Excel or CSV document, organizing the various connection types with their mechanical properties, overstrength factors, etc. Some of these may not yet be known, this will either be filled in arbitrarily and marked as such or left blank.

The seismic design parameters will be provided as dropdown input on the Grasshopper interface, separate from the main analysis script. This will allow for other standards to be supplemented into the computational workflow. Maximum deformations will also be included as an input here.

Modelling Strategy

If the building model input, connections layout, and components database are provided as described above, a Grasshopper script will automatically generate an analysis model per the referenced modelling strategy (Rinaldi et al. 2021).

The CLT shearwalls will be modelled as two-dimensional elements with horizontal strips representing the connection zone and the floor properties.

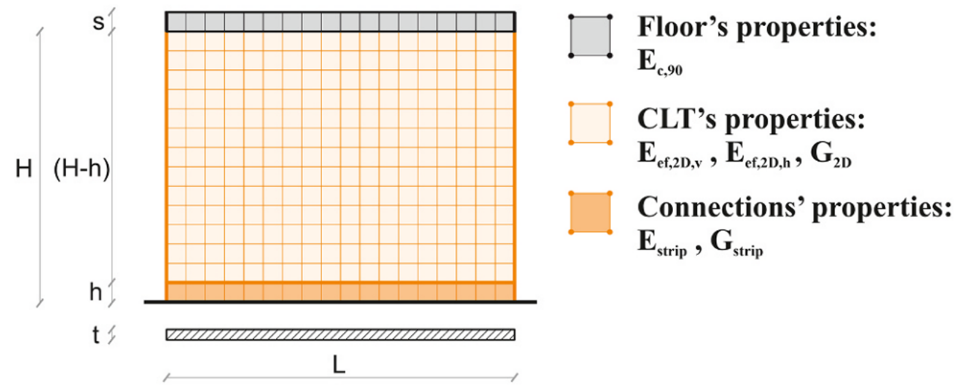


Figure __ – CLT shear wall modelling strategy, 2D elements (Rinaldi et al. 2021)

Equivalent stiffnesses are calculated for the wall elements to included effects from both sliding and rocking deformation. Friction contribution is neglected, which is a conservative approach (friction helps reduce deflections).

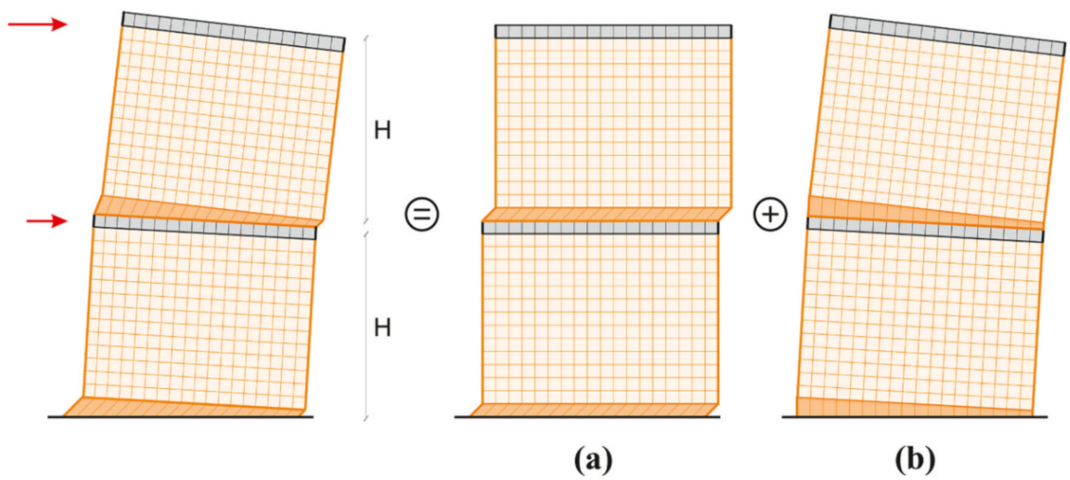


Figure __ – Multi-story wall deformation, contributions from (a) sliding and (b) rocking (Rinaldi et al. 2021)

This modelling strategy has slightly different equations for single panel vs multi-panel shear walls, because rocking behavior for multi-panel walls is considered negligible.

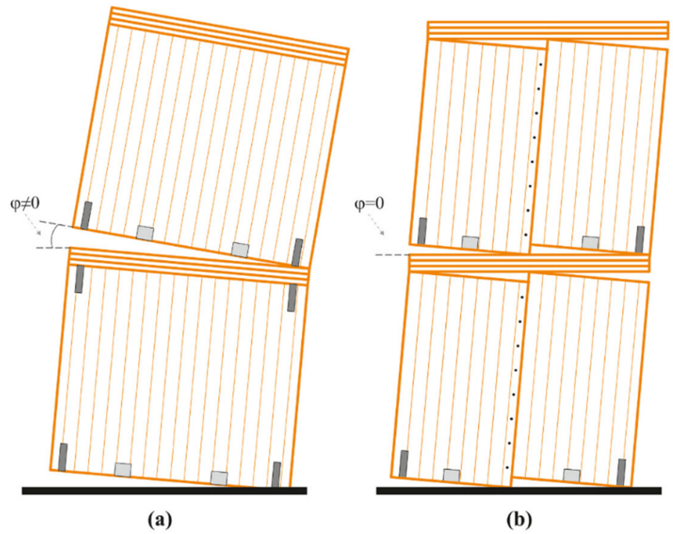


Figure __ – The deformation from rocking behavior for (a) single-panel walls vs (b) multi-panel walls (Rinaldi et al. 2021)

Initial Analysis

The initial analysis phase of the computational workflow will be used to determine the original design, using an iterative workflow process until the deformations are with the limits set by the code.

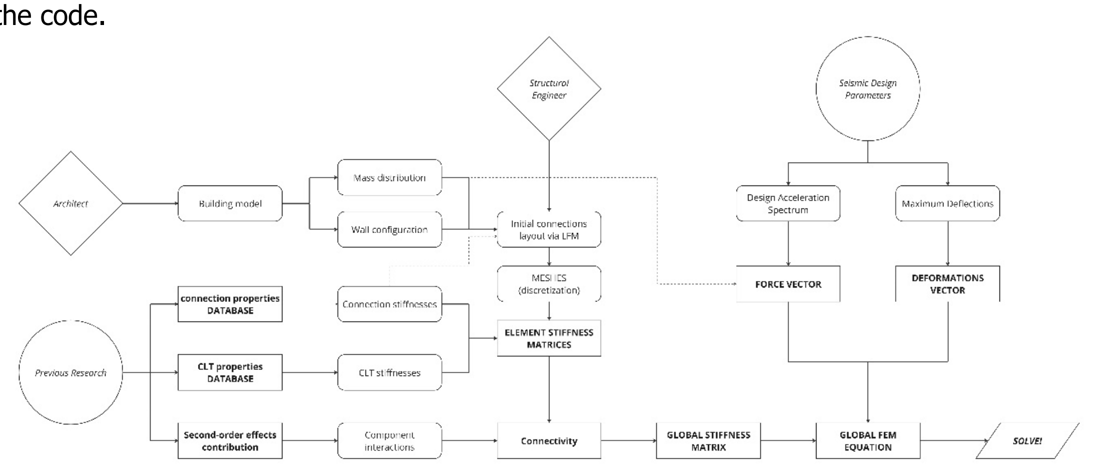


Figure __ – Flowchart for initial analysis

Lifetime Analysis
The secondary analysis phase will include a service life analysis with changing stiffness and masses based on the time- and event-based parameters.

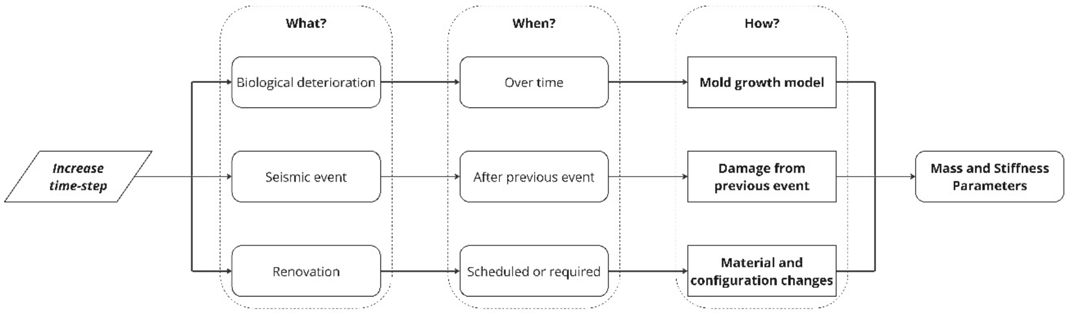


Figure __ – Flowchart for secondary analysis

Output Structure
The output will provide the engineer with initial and service life data of each wall and its connections. It will pinpoint moments in time where renovations or retrofit will be required to effectively extend the life of the building.

Reflection

1. What is the relation between your graduation (project) topic, the studio topic (if applicable), your master track (A,U,BT,LA,MBE), and your master programme (MSc AUBS)?
2. What is the relevance of your graduation work in the larger social, professional and scientific framework?

This graduation project aims to advance knowledge in the field of seismic analysis for tall timber structures by developing a practice-oriented computational workflow. The workflow will facilitate a more seamless integration of seismic analysis into the overall design process of tall timber buildings. Additionally, it will incorporate variable parameters impacting stiffness and mass of the structure over time, to enable a multifaceted service life analysis of the structure's seismic behavior. To achieve accurate predictions, input from various disciplines will be essential—such as assessing how facade design influences moisture damage in timber. These interdisciplinary considerations align closely with the core values of the Building Technology program. Furthermore, the workflow will provide the ReStruct group with a comprehensive database of the latest experimental data on the strength of timber and its connections.