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FORCED RESPONSE MEASUREMENTS ON A SEVEN STOREY TIMBER BUILDING IN SWEDEN

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ABSTRACT: Forced vibration tests have been conducted on the seven-storey timber building Eken in Mariestad in Sweden. The main objective is to estimate the building's dynamic properties from test data. The eigenfrequencies, mode shapes and their scaling are useful to calibrate numerical models. However, the most important outcomes are the estimates of the modal damping values. The reason is that the damping impacts the acceleration, and thus the serviceability of the building, and at the same time, it is very hard to model damping. So, during the design phase, one must rely on previous test data (of which very few exist for taller timber buildings) or rule of thumbs. It is therefore important to gain knowledge about the damping for timber buildings in order to enable good designs of future and taller timber buildings. The test data shows that the modal damping is roughly equal to 2% of the critical viscous ones for the eigenmodes extracted. The test campaign on Eken is made as a part of the project Dyna-TTB in which vibrational tests have been performed on eight high-rise timber buildings, in Europe, of which Eken is one.

KEYWORDS: Forced vibration, timber building, damping, eigenmodes, experimental modal analysis, Dyna-TTB

1 INTRODUCTION

Within the project Dyna-TTB, measurements on eight multi-storey timber buildings around Europe have been conducted to gain more knowledge on their dynamic performance at serviceability level. The dynamic response of a structure is governed by four quantities: the mass, the damping, the stiffness, and the dynamic load. The damping is the one that is hardest to predict; reliable models are rare and most often the damping is taken from tests or as one value of modal viscous damping taken from rule of thumbs. One of the primary objectives of the Dyna-TTB project is to broaden the knowledge base regarding damping in timber buildings. Such a data base is useful during the development of future, possibly even taller than the tallest today, high rise timber buildings. For modelling purposes, it is also important to have information regarding resonance frequencies, mode shapes and modal masses. The Swedish case study in the DynaTTB project was the seven-storey building Eken (the Oak in English), see Figure 1. For more information on the DynaTTB project see [1]. Examples of other measured buildings in the DynaTTB project can be found in [2]–[5].

The purpose of vibration tests is to get measures of resonance frequencies, to estimate damping, mode shapes and modal masses. The test set-up answers the questions how to excite a structure as well as how and where to measure responses.

The models used to calculate accelerations due to wind loads, in the serviceability limit states, vary between different codes [6]. However, all of them are based on the same concept; only the first bending mode is included. If one assumes the shape of the first bending mode to be known and that the first resonance frequency is associated with the first bending mode, one accelerometer is sufficient to get the desired information. More sensors are beneficial but not necessary. However, to get data for model calibration, several spatially resolved mode shapes are needed or at least most desired. Furthermore, there are many ways of exciting a structure. Forced response measurements have the advantage that they enable scaling of the mode shapes. Shaker excitations are commonly used in forced vibration measurements. It is important that all the excitations stem from the shaker or shakers in the intended directions and that the stimuli are measured. Among different signals that can be used for the shaker excitations, stepped sine testing has the advantage of focusing all the energy in one frequency at the time, which is beneficial when large structures are excited by limited forces.

When creating an FE-model, here representing a multi-storey timber building, important input parameters are the

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stiffnesses and masses of the different parts of the building system. One example of important parameters is the stiffnesses of connections. This has also been studied in the DynaTTB project [5], [7], [8].

This paper describes the forced vibration test campaign on the building Eken in Sweden. The measurement campaign was performed in the spring of 2022. The paper also presents some of the test results in the form of frequency response functions (FRFs) and modal properties for some of the extracted modes.

2 THE BUILDING EKEN

The building Eken was finished in 2019 and contains 31 rental apartments. It is in the city of Mariestad in the south part of Sweden, see Figure 1. The height, width and depth of the building are 24, 27 and 19 m respectively. The building was built by the company Stenmarks Bygg and it is owned by Mariehus.

2.1 THE BUILDING SYSTEM

Half of the bottom floor is made of concrete whereas the other half, the other storeys and the elevator shaft are made of timber. The building is built using the Moelven Trä 8 system [9]. The load bearing system consists of glued laminated timber (glulam) beams and columns whereas glulam trusses form the stabilizing elements, see Figure 1. In total the structure consists of 12 glulam trusses, four in the weak direction of the building and eight in the strong direction of the building. The glulam trusses are, in principle, symmetrically located in the building and the trusses in the middle go through all seven storeys of the building.

The floor system is made of strengthened LVL sheets acting as a diaphragm system. The connections in the glulam trusses are slotted-in-steel-plates fastened with steel dowels. The other glulam beams are fastened using steel hangers screwed to the gluelam members. These glulam building components are manufactured and assembled by the company Moelven Töreboda.

The apartments are vibrationally isolated from each using a thin concrete screed resting on sound insulation on top of the LVL floors. The floors are separated in all apartment separating walls. The internal walls and ceilings consist of gypsum wall boards on acoustic studs.

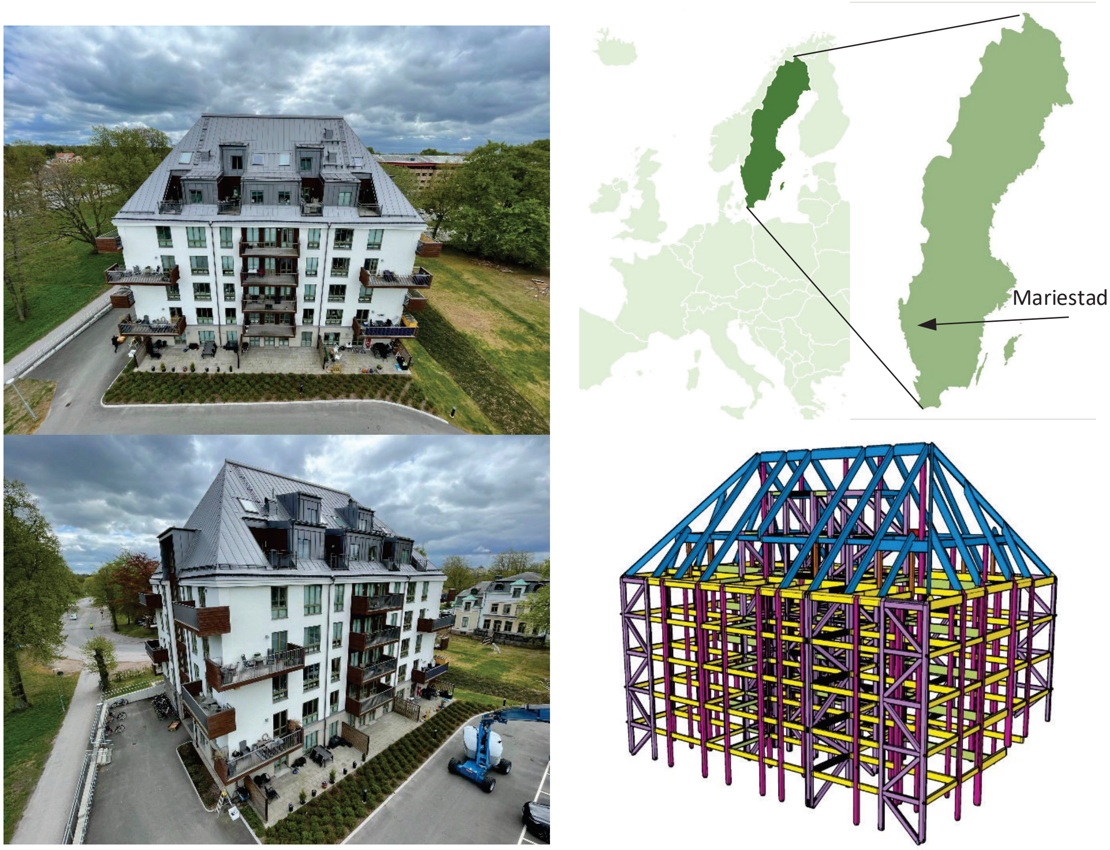

__Figure 1.__ The Eken building in Mariestad with images of the finished building, its location in Sweden and the glulam parts of its structural system.

2.2 The test set-up

The dynamic performance of the building Eken has been studied during the measurement campaign using a forced vibration set-up. Forced vibration tests have the benefit of enabling more precise damping estimates than ambient vibration tests. It also renders in e.g., scaled accelerances. Mass inertia forces can be used to excite buildings in forced vibration tests. For that purpose, an APS 420 shaker was used in the Eken measurement campaign, see Figure 2. The shaker was placed in the ventilation room on the top (seventh) floor. Due to the heavy weight (140 kg) of the shaker, it had to be lifted using a crane through a roof window, see Figure 6. To properly excite the building structure, the shaker was bolted to a specially produced steel plate, that was screwed through the floor to one of the main glulam beams and clamped around one of the main glulam columns that runs vertically through the whole building, see Figure 2. The steel plate was prepared to allow for three positions of the shakers to excite the building along its main axis, perpendicular to its main axis and at 45º.

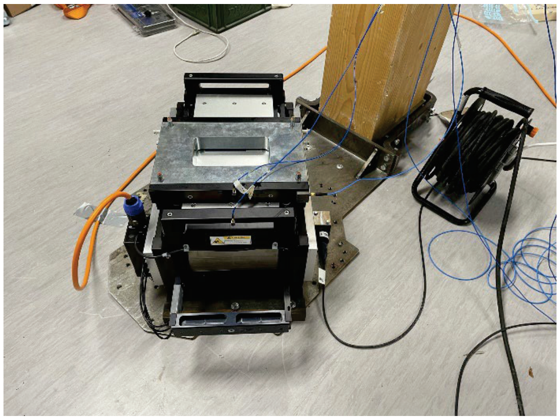

Figure 2. *Excitation by mass inertia, using an APS 420 shaker, used for stepped sine excitation, fastened to a steel plate fastened to the main glulam structure using screws. In this set-up the shaker is placed in a 45° angle to the buildings main axis.*

In total 45 accelerometers: PCB 393B12 and PCB 393M62, with the sensitivity 10V/g, were used to measure the response of the building at different places and different directions. The main configuration of the accelerometers was two accelerometers, mounted on small steel cubes, placed on the building to measure the responses in two orthogonal directions, see Figure 3. The steel cubes with the accelerometers were screwed directly on the structure of the building at four different levels at each of the four corners of the building, under the balconies, see Figure 4, and two positions under the main roof beam at the top of the building. There were also accelerometers placed on the top floor close to the shaker and in the staircase.

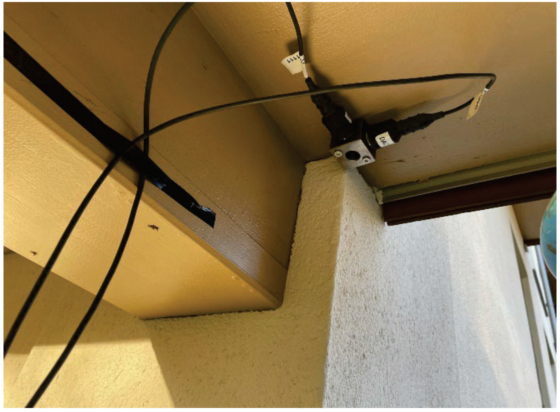

Figure 3. *Two PCB-39 accelerometers positioned under a balcony at one of the corners of the building.*

Three Siemens Scadas data acquisition (DAQ) units, connected via fiber-optic cables, were used to control the excitation and to collect measurement data. One of the boxes was placed in the room where the shaker was located, and it controlled the other two boxes located at the ground outside the building. Each DAQ was put into a plastic box for weather protection and the boxes communicated with the accelerometers via cables, see Figure 5. The accelerometers, cables and the Siemens Scadas data acquisition cables were installed using a 25 m tall skylift, see Figure 7.

Figure 4. *Positioning of sensors, with four accelerometer positions along the height in the four corner of the building and two accelerometer positions under the roof (red boxes) and the shaker at the attic room attached to one of the glulam columns.*

Figure 5. *One of three Siemens Scadas Acquisition boxes.*

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2.3 The forced vibration test of the building

The forced vibration test was performed using a stepped sine test set-up. Stepped sine testing has the advantage of focusing all the energy in one frequency at the time. Here, an APS 420 (APS Dynamics) inertia shaker was used for stepped sine testing from 2 Hz to 20 Hz. The excitations were made in 0, 45 and 90 degrees in relation to the axis along the width of the building. The steel plate, under the shaker, was used to connect the shaker directly to the load-bearing structure. The accelerometers were also placed directly to the main glulam structure. Thus, the force was made likely to excite the global modes of the building.

The total recording time for a stepped sine test, going from 2Hz to 20 Hz with a step size of 0.01 Hz took about four hours. Thereafter the direction of the shaker was changed to another angle and the test was repeated. This was made to make sure that all modes in the frequency range were captured.

Figure 6. *Lift off the 140 kg shaker from the ground to the top floor position through a small attic window.*

Figure 7. *Installation of cables and accelerometers in progress using a 25 m sky-lift.*

3 RESULTS

The test data were evaluated using the software Siemens Test Lab. The evaluated parameters in this first basic evaluation were:

- resonance frequencies,
- modal damping,
- mode shapes and
- modal masses.

The data evaluated were in the form of FRFs from which the modal properties were estimated. The quality of the estimates was examined by a comparison between the measured FRFs and the synthesized counterparts. The part of the direct point receptance for excitation in the Y-direction (the flexible direction) that includes the first three resonance frequencies, is shown in Figure 8.

The first bending mode in the weak direction was found to have a frequency of 2.4 Hz. The next mode is a torsional mode at 2.7 Hz.

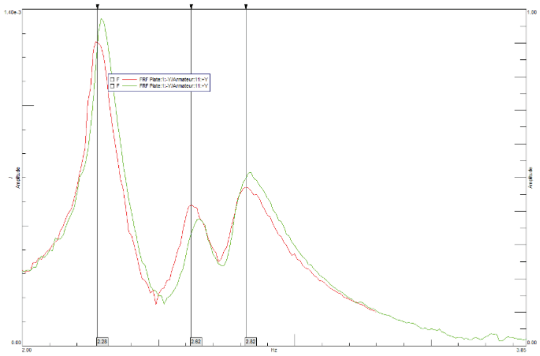

Figure 8. *An FRF stemming from excitation in the Y-direction (the flexible direction). The first three resonances are shown, x-axis scale 2-3 Hz.*

To verify that a sufficient frequency resolution is used, a Nyquist plot is useful, see Figure 9. The plot shows the frequency range including the first three resonance frequencies.

The damping could be evaluated for these modes. A preliminary estimation showed that the relative viscous damping was 1.6% for the first bending mode in the weak direction (at 2.4 Hz). The first torsional mode was found to have a relative viscous damping of 1.9% (at 2.7 Hz). The second bending in the flexible direction had 1.6% damping at 7.0 Hz.

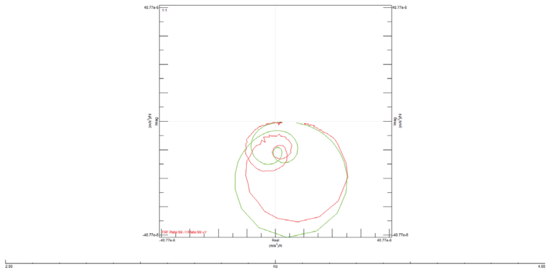

Figure 9. *Nyquist plot for an FRF stemming from excitation in the Y-direction (the flexible direction). The first three resonances are shown.*

Scaled mode shapes were also extracted from test data. An AutoMAC was calculated, and it shows that the mode shapes extracted from the test data are very close to orthogonal. The modal parameters will be used to calibrate an FE-model representing the building. It was possible to find fifteen distinguishable modes in the frequency range 2-20 Hz when exciting the building in the Y-direction (the flexible direction), see Figure 10.

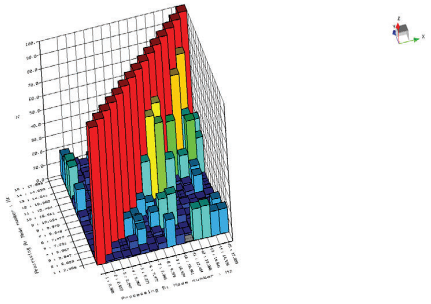

Figure 10. *AutoMAC for modes stemming from excitation in the Y-direction (the flexible direction). There are fifteen distinguishable modes in the frequency range 2-20 Hz.*

When exciting the building in the X-direction (the stiff direction), there were ten distinguishable modes in the frequency range 2-20 Hz, see Figure 11. Some of the modes are the same in the sets stemming from excitation in the X- and Y-directions. In total around twenty separate modes could be seen in the data.

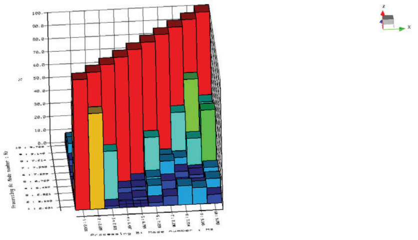

Figure 11. *AutoMAc for modes stemming from excitation in the X-direction (the stiff direction). There are ten distinguishable modes in the frequency range 2-20 Hz.*

The plots of mode shapes, see Figure 12, Figure 13 and Figure 14, show the first bending mode in the Y-direction, the first torsion mode and the second bending mod in the Y-direction. The first bending mode is very symmetric and shows an almost pure bending of the building.

The torsion mode shows a mode shape that is almost symmetric but with the rotation center moved slightly from the center of the building. This is due to that the trusses are not placed perfectly double symmetrical.

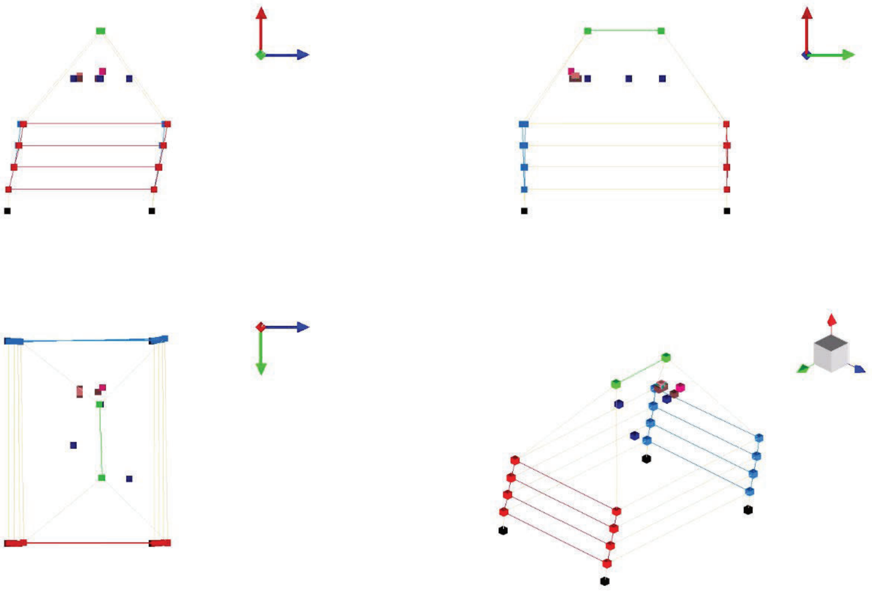

Figure 12. *The first bending mode in the Y-direction (the flexible direction).*

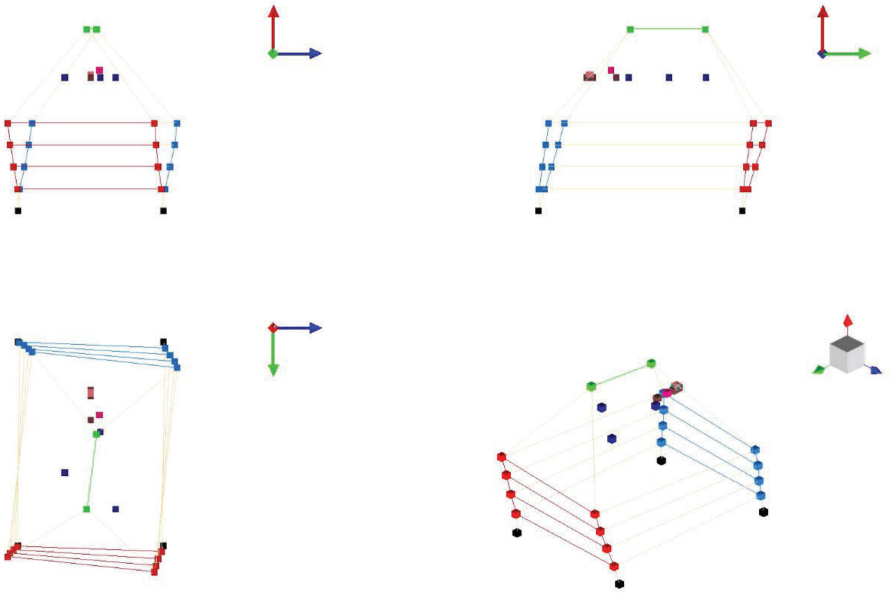

Figure 13. *The first torsion mode.*

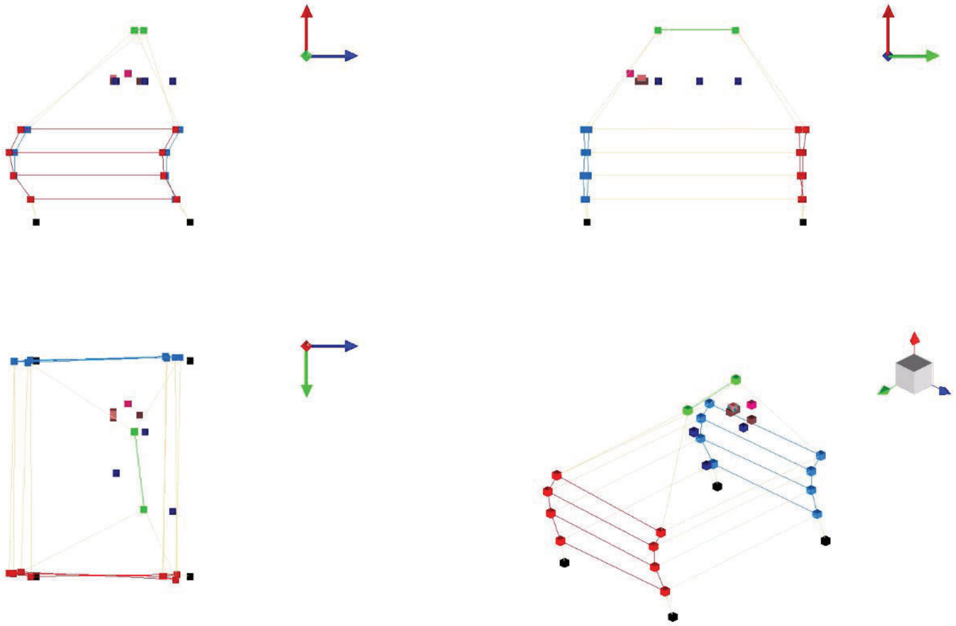

Figure 14. *The second bending mode in the Y-direction (the flexible direction).*

The most important outcome is the contribution to the knowledge base regarding damping in high-rise timber buildings. The damping values are roughly 2% for the modes extracted, see examples in Table 1. That knowledge is valuable in the design work of future and taller timber buildings.

Table 1. *Resonance frequency and relative viscous damping for three vibration modes.*

Mode	Resonance frequency	Damping relative viscous
1st bending, flexible direction	2.4 Hz	1.6%
1st torsion	2.7 Hz	1.9 %
2nd bending, flexible direction	7.0 Hz	1.6 %

4 CONCLUSIONS

In this paper, the vibrational test campaign made on the seven-story timber building Eken in Mariestad in Sweden is presented. By using mass inertia forces generated by an APS 420 shaker in combination with sensitive accelerometers, 10 mV/g, the fundamental and global modes were successfully extracted from test data even when the excitation force amplitude was low. The estimated damping values agree with estimated damping values from other test campaigns within the project Dyna-TTB. The results contribute to the knowledge base regarding damping in high-rise timber buildings and are thus useful for future design of tall timber buildings.

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REFERENCES

[1] R. Abrahamsen, M. A. Bjertnaes, J. Bouillot, B. Brank, and L. Cabaton, "Dynamic response of tall timber buildings under service load-the dynattb research program," Nov. 2020. [Online]. Available: http://urn.kb.se/resolve?urn=urn:nbn:se:lnu:diva-99080

[2] B. Kurent, B. Brank, and W. K. Ao, "Model updating of seven-storey cross-laminated timber building designed on frequency-response-functions-based modal testing," *Structure and Infrastructure Engineering*, 2021, doi: 10.1080/15732479.2021.1931893.

[3] B. Kurent, N. Friedman, W. K. Ao, and B. Brank, "Bayesian updating of tall timber building model using modal data," *Eng Struct*, vol. 266, p. 114570, Sep. 2022, doi: 10.1016/J.ENGSTRUCT.2022.114570.

[4] M. Manthey, O. Flamand, A. Jalil, A. Pavic, and W. K. Ao, "Effect of non-structural components on natural frequency and damping of tall timber building under wind loading," *World Conference on Timber Engineering 2021, WCTE 2021*, 2021.

[5] S. Tulebekova, K. A. Malo, A. Rønnquist, and P. Nåvik, "Modeling stiffness of connections and non-structural elements for dynamic response of taller glulam timber frame buildings," *Eng Struct*, vol. 261, Jun. 2022, doi: 10.1016/J.ENGSTRUCT.2022.114209.

[6] P. Landel, M. Johansson, and A. Linderholt, "Comparative study of wind-induced accelerations in tall timber buildings according to four methods," in *World Conference on Timber Engineering 2021, WCTE 2021*, 2021.

[7] P. Landel, "Wind-induced vibrations in tall timber buildings : Design standards, experimental and numerical modal analyses," Licentiate Thesis, Linnaeus University, Växjö, 2022.

[8] P. Landel and A. Linderholt, "Reduced and test-data correlated FE-models of a large timber truss with dowel-type connections aimed for dynamic analyses at serviceability level," *Eng Struct*, vol. 260, Jun. 2022, doi: 10.1016/J.ENGSTRUCT.2022.114208.

[9] Moelven, "Flervåningshus Trä8." https://www.moelven.com/se/produkter-och-tjanster/allt-om-limtra/flervaningshus-tra8/ (accessed Feb. 02, 2023).