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DYNAMIC RESPONSE OF TALL TIMBER BUILDINGS UNDER SERVICE LOAD – RESULTS FROM THE DYNATTB RESEARCH PROGRAM

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ABSTRACT: Wind-induced dynamic excitation is a governing design action determining size and shape of modern Tall Timber Buildings (TTBs). The wind actions generate dynamic loading, causing discomfort or annoyance for occupants due to the perceived horizontal sway, i.e. vibration serviceability problem. Although some TTBs have been instrumented and measured to estimate their key dynamic properties (eigenfrequencies, mode shapes and damping), no systematic evaluation of dynamic performance pertinent to wind loading had been performed for the new and evolving construction technologies used in TTBs.

The DynaTTB project, funded by the ForestValue research program, mixed on site measurements on existing buildings excited by mass inertia shakers (forced vibration) and/or the wind loads (ambient vibration), for identification of the structural system, with laboratory identification of building elements mechanical features, coupled with numerical modelling of timber structures. The goal is to identify and quantify the causes of vibration energy dissipation in modern TTBs and provide key elements to finite element models. This paper presents an overview of the results of the project and the proposed Guidelines for design of TTBs in relation to their dynamic properties.

KEYWORDS: Timber building, wind load, forced vibration, discomfort, modelling, damping, full scale.

1 INTRODUCTION

1.1 Background

The complexity of the design and the construction of buildings increases with their height and the number of storeys. Tallness is relative to experience, situation, or context so the definition of a Tall Timber Building (TTB) cannot be universal. Complexity is found in the production on the construction site due to a high building's height but also in the need for extra technical systems and control. The increased height means higher vertical loads caused by higher weight but also significantly higher horizontal wind loads. For taller structures, the wind load can generate dynamic effects on the structure which must be included in the serviceability design.

1.2 Building system for TTBs

The studies in the Dynamic Response of Tall Timber Buildings Under Service Loads (DynaTTB www.dynattb.com) project show that TTBs, due to their low masses compared to steel and/or concrete buildings, are sensitive to wind loads in the serviceability limit state. The building height where sway is necessary to consider in the design of the structural system is lower than for other building materials such as steel or concrete. The number of storeys where wind-induced vibrations govern the design vary dependent on the building system, building shape and wind speed in the actual location. In zones with high wind velocity and buildings with a larger height to width ratio, it can be a good practice to check the acceleration levels at the highest floor for buildings as low as six storeys in order to check the serviceability limit state criteria [1], [2].

TTBs can be built with several different building systems introducing different difficulties during design and construction. The most common building systems for TTBs are planar elements, beam-column systems with trusses and hybrid systems utilising a combination of materials for the load bearing structure, see Figure 1.

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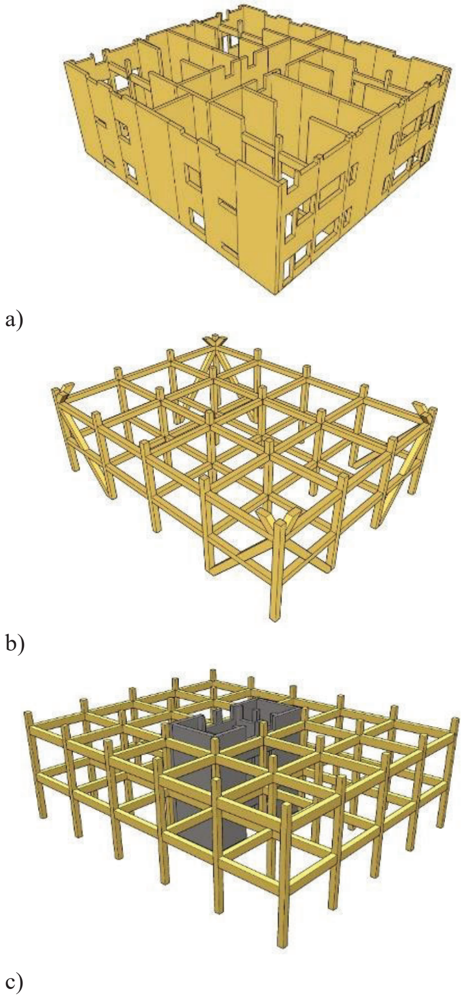

Figure 1: *Typical building systems for TTBs; a) planar elements, b) beam-column systems with trusses and c) hybrid systems using a combination of materials in the load bearing structure.*

1.3 Acceleration and code calculations

The limiting factor in serviceability limit state (SLS) design is in most codes the peak acceleration at the top floor of the building. Often the limit for the acceleration defined in ISO 10137 [1] as the maximum peak acceleration, caused by a wind velocity level with a one-year recurrence period is used. The recommended upper acceleration limits are higher for office buildings than for residential buildings. The maximum acceleration limit is an SLS requirement and is therefore an issue that should be agreed upon in the contract between the property owner and the engineers/contractor.

The codes provide recommendations for how to calculate the along-wind accelerations, as for example in annex B and annex C in Eurocode [2]. These calculation models are built on four types of parameters:

i) the wind velocity and terrain,
ii) the geometry of the building giving the force coefficient,
iii) the aerodynamic properties of the building, and
iv) the mechanical properties of the building.

Some of these parameters are related to the properties of the structure of the building. These parameters are necessary for the actual building and are estimated using a simulation model, often a finite element (FE) model. These structural parameters are:

- the natural frequencies for the bending modes in the two main directions of the building,
- their mode shapes and
- their related modal masses.

The last parameter necessary for the calculation of the along-wind accelerations is a value for the modal damping, which is difficult to model. Therefore, an estimated/measured value must be used. Within the DynaTTB project the modal damping values of eight timber buildings with different structural systems in several European countries have been measured and evaluated, see Table 1.

1.4 The DynaTTB project

The project DynaTTB; Dynamic Response of Tall Timber Buildings under Service Load, ran between 2019 and 2022 with partners from France, Norway, Slovenia, Sweden, and the UK. The main objective of the project was to experimentally identify a number of full-scale TTB structures (finished or currently being built) and, based on these, develop representative FE models for predicting the vibration response of TTBs exposed to wind-induced dynamic loading. The project represents the first systematic evaluation of dynamic performance pertinent to wind loading in the world for TTBs using, in addition to ambient vibration tests, also forced vibration tests. The main results have been included in a Guideline for practicing engineers on how to design TTBs subjected to wind loads in the Serviceability Limit State (SLS). Results have also been disseminated through scientific journals and seminars/conferences. This paper presents an overview of the results and the main structure of the guidelines. More detailed results can be found in [3]–[6] which will be presented at the WCTE 2023 conference. Other results can be found in for example [7]–[15].

2 DESCRIPTION OF BUILDINGS

In the project, a total of eight buildings, see Figure 1, have been tested using, in addition to preliminary ambient vibration tests, also forced vibrations to estimate their dynamic properties: eigenfrequencies, normalized modes shapes and damping. One more building has been tested using Ambient excitation and three of the buildings have also been equipped with long-term monitoring equipment.

The buildings vary in height from four to eighteen storeys with several building systems to represent TTBs in Europe today.

Figure 2: *The buildings tested and their location in Europe.*

Table 1: *Description of the tested buildings.*

	Building 1	**Building 2**	**Building 3**	**Building 4**	**Building 5**	**Building 6**	**Building 7**	**Building 8**
Name	Trinity round church	Flower valley	Inno Renew	Eken	Yoker[2]	Treed-it	Hyperion	Mjøstårnet
Location	UK	Slovenia	Slovenia	Sweden	UK	France	France	Norway
Number of storeys	4	4	4	6	7	12	17	18
Building system	Planar elements	Planar elements	Planar elements	Beams and columns+ trusses	Planar elements	Hybrid	Hybrid	Beams and columns+ trusses
Building height [m]	16 m	12.7 m	16.7 m	24.4 m	22 m	36 m	57 m	85.4 m
Height to highest habituated floor [m]	~12 m	8.9 m	12.5 m	18.0 m	18 m	33 m	50 m	68.2 m
Building width [m]	14 m	14.5 m	23.6 m	27 m	31 m	47.4 m	30.6 m	36.8 m
Building depth [m]	33 m	21.2 m	38.7 m	19 m	28 m	18.6 m	19.1 m	16.3 m

3 CASE STUDIES

This section shortly presents results from three case studies, built with different building systems and of different heights. The presented results include the first natural frequencies, an example of a captured mode shape and a damping value. The three buildings are:

- the seven storey, full CLT building Yoker in UK,
- the seven storey, glulam post and beam structure Eken in Sweden,
- the seventeen storey, hybrid building Hyperion in France.

3.1 Yoker building, UK (CLT structural system)

The building Yoker is located in Glasgow, UK. The building is designed by Smith and Wallwork Ltd and it is built using cross-laminated timber (CLT) from Stora Enso company. The characteristic dimensions of the building are: 31m by 28m in plan, 22m in height above the ground floor slab, 3745m^2 gross floor area, and 550m^2 footprint area. The building is T-shaped with three “wings” and a centrally located stair and elevator shaft. The building was designed using CLT panels in a platform building system, see Figure 3. Five different types of CLT panels were used, varying in thickness from 100mm to 140 mm (except for the stair half-landing with 200mm CLT

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[2] The building consist of three wings and the measurement gives the maximum extreme points of the building.

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panels), having either 3 or 5 layers were used. The external walls (as well as some internal walls) consist of large CLT panels which have the height of the storey and the length of the building edge, with pre-cut openings for windows. The CLT panels in the Yoker building are typically connected using a combination of angle brackets and wood screws. For more details of the buildings, see [14].

Figure 3. *The main structure of the Yoker building, showing the distribution of the CLT panels in the external walls.*

The dynamic testing of the building was performed using three synchronised APS Model 400 electrodynamic shakers with a total moving mass of 68.85 kg, which were installed on the 6th floor. Altogether 13 sensor locations were chosen with 2 sensor locations on each floor and an additional one on the 6th floor as a reference sensor near the shakers. Each sensor location measured accelerations in two horizontal directions. At the time of the measurements, the building was operational, so installation of the sensors was limited to the corridors in the core of the building. The measurements were performed by researchers from University of Exeter.

An FE-model was built for the structure using the following assumptions: (i) the foundation is rigid and fixed, (ii) the connections were not explicitly modelled, and (iii) the floors are flexible (i.e. the assumption of the rigid-diaphragm is not used). The initial shape for the first bending mode is shown in see Figure 4. The model was updated based on the measurement results in the next phase. The updating showed that shear stiffness of the CLT walls is higher than anticipated by the initial model. Furthermore, the analysis showed that vertical stiffness of the building is lower than initially estimated. The modelling was performed by researchers from University of Ljubljana, for more details of the modelling see [14].

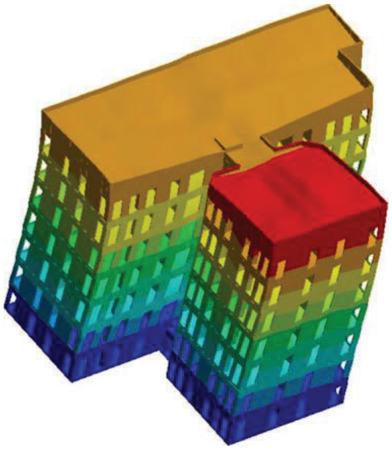

Figure 4. *First mode shape from the FE-analysis.*

The modal properties from the measurement on the Yoker building showed that the first bending mode (including some torsion) had a natural frequency of 2.85 Hz with a relative viscous damping of 1.4%, see [16]. The results also showed that the damping was frequency dependent.

3.2 Eken building, Sweden (Glulam truss structural system)

The building Eken was finished in 2019 and contains 31 rental apartments. The height, width and depth of the building are 24 m, 27 m and 19 m, respectively. The building was built by the company Stenmarks Bygg, and it is owned by Mariehus. The building is built using the Moelven Trä 8 system [17]. The load bearing system consists of glued laminated timber (glulam) beams and columns whereas trusses form the stabilizing elements, see Figure 5Figure 1. The total structure consists of 12 glulam trusses, four in the weak direction and eight in the strong direction of the building. The glulam trusses are in principle symmetrically located in the building and in the centre of the building they stretch from the concrete foundation 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 in the glulam beams. These glulam building components are manufactured and assembled by the company Moelven Töreboda.

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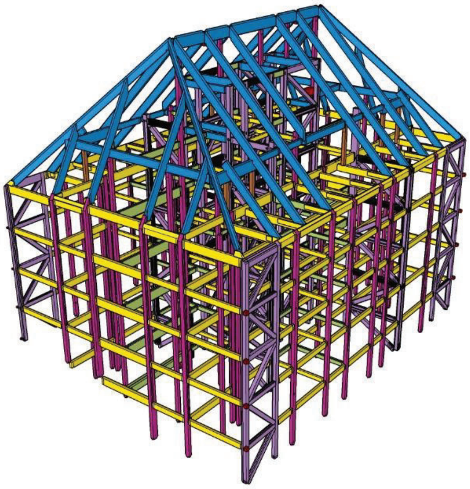

Figure 5. Glulam structure of the building Eken.

The dynamic performance of the building Eken has been studied during the measurement campaign using a forced vibration set-up. For that purpose, APS 420 shaker was used, and it was placed on the top (seventh) floor in the ventilation room. In total 45 accelerometers were used to measure the response of the building at different places and directions. The accelerometers were placed at four different levels at each of the four corners of the building, under the balconies, and two positions under the main roof beam at the top of the building. The first bending mode in the weak direction was found to have a frequency of 2.4 Hz. The measurements were performed by Linnaeus University.

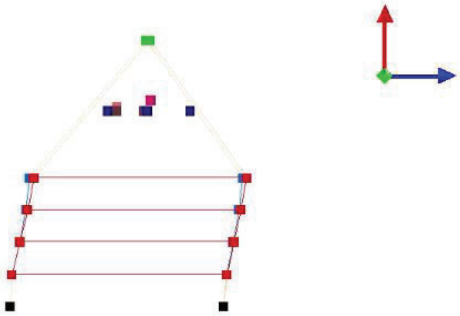

Figure 6. Modes shape for the first bending mode.

The first mode was a pure bending mode in the weak direction of the building, see Figure 6. The damping could be evaluated for each resonance frequency. A preliminary evaluation showed that the relative viscous damping was 1.6% for the first bending mode in the weak direction. More details of the measurements can be found in [3].

3.3 Hyperion, France (Hybrid structural system)

The Hyperion Tower, located in Bordeaux, is one of the tallest mass timber buildings in France with 57m height and 17 storeys. It was built by the Eiffage Construction company following a design by Jean-Paul Viguier architect and SETEC structural design office. It is a private housing which is distinguished by its 141 large balconies, made of steel. As for the majority of French buildings using timber it is a hybrid structure, i.e. a central concrete core gives the main resisting part to horizontal loads and satisfies the local fire safety requirements. In Hyperion Tower all floors and horizontal beams are made of CLT, the façade itself uses wood panels as stiffeners.

Mode shapes, frequencies and damping have been measured using excitation by a heavy mass shaker [11], [12] with a 550 kg moving mass allowing large amplitude displacements, used for the evaluation of damping at various stages of amplitude. The first natural frequency of the building was 0.91 Hz with a mode shape as shown in Figure 7.

An FE model was built with ANSYS [13] and used to prepare the testing session as well as checking that the shaker would not overload the structure.

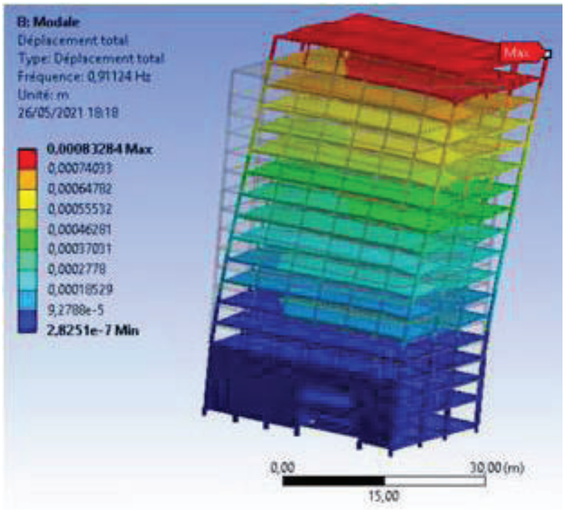

Figure 7. Mode shape for the first bending mode from the FE-model.

The FE-model was improved to match the results from the on-site testing, providing a reliable digital twin of the real building. The building was finally equipped with a long-term monitoring system including the measurement of wind 10 m above the roof, in order to check the dynamic behaviour under strong wind. The modelling and measurements were performed by CSTB.

4 GUIDELINES FOR SLS DESIGN OF TTBs

4.1 Overview of the Guidelines

The aim of the guideline is to give recommendations to structural engineers designing TTBs, but is also aimed at manufacturers of timber building systems, property developers interested in building taller with wood and researchers dealing with dynamic effects on TTBs. The focus is on the design for the serviceability limit state (SLS) of tall buildings with timber structures, their

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dynamic properties and how wind-induced vibrations can be mitigated. There are several books that describe general design of TTBs, especially with focus on ultimate limit state [18], [19] as well as guides for modelling timber structures [20].

The results of the project will be collected into a written guideline with the tentative title: **Dynamic Properties of Multi-Storey Timber Structures for Wind-Induced Vibrations: Case Studies of Full-Scale Testing and Modelling.**

The general structure of the guidelines will be:

1. Guidelines on calculation of wind-induced vibrations
2. State-of-the-art
    2.1 Tall timber building systems
    2.2 Wind loads requirements in serviceability limit state
    2.3 Dynamic testing of tall timber buildings
    2.4 Modelling of tall timber buildings for dynamic response in SLS
3. Building case studies
    3.1 Building A
    3.2 Building B
    3.3 Building …
    3.N Building N

4.2 Recommendations for FE-modelling of TTBs

The FE-models established for evaluating the SLS response should provide as a minimum result at least the following parameters: the first natural frequency in bending in the two main lateral directions of the building, their associated mode shapes and the equivalent, or modal, masses.

Based on the project outcomes, the following recommendations can be given when creating an FE-model of a TTB for SLS design:

- Use mean values for density of materials and nominal dimensions of structural elements.
- Use mean values for stiffness of material.
- Masses of non-structural elements should be included in as accurate location as possible.
- Most probable value for live load should be included in the model. Actual live load can be significantly lower than the values recommended in building codes, such as Eurocode 1 [21].
- For structures using planar wood elements, walls and floors are recommended to be modelled including openings.
- For buildings designed using a platform structural system, perpendicular to the grain flexibility of floor slabs is recommended to be included in the model.
- Connections that exhibit semi-rigid behavior in SLS in both translational and rotational directions should be included in the model. As a starting point connection stiffnesses calculated according to Eurocode 5 [22] can be used.
- For hybrid buildings with concrete cores and/or timber concrete floors, average material values representative for the concrete elements are considered. Assumptions made for dynamic seismic models (cracked concrete, etc.) are not relevant.
- For composite timber-concrete floors, the rigid diaphragm assumption can be considered provided that the minimum concrete thickness required for this assumption is verified (see ETA document of considered floor system).
- The horizontal and vertical stiffnesses of the foundation can have a large impact on the results. Soil parameters such as stiffness, damping, etc. are strain rate dependent. Reference values from seismic analysis should be adjusted for SLS verifications.
- Contribution of stiffness of non-structural elements should be explored as their impact on the modal response of the building has been observed.

In general, it is on the safe side to assume conservative mass and stiffness values for the building when creating the model. There are large uncertainties in the FE-models, especially regarding the effect of stiffness of connections, foundation, and the contribution from non-load bearing elements. It is therefore advised to do a sensitivity study for the effect of these parameters on the results.
An FE-model can also be used to estimate the acceleration levels directly if the model can include a representative wind load model.

4.3 Recommendations for on-site measurements

The current number of TTBs completed in the world is still relatively low. Hence, there is still a lot of uncertainties in the modelling, design and construction of these kinds of structures. It is therefore important to measure and evaluate completed structures to investigate the accuracy of the models and update the recommendations and the best practice for modelling TTBs in SLS. The current codes and standards used today also have very limited information on how to model TTBs and on values to be used for example for modal damping in tall timber structures in SLS. To create a statistical basis for a recommended value for damping to be used in the codes, it is necessary to evaluate the modal damping in more completed TTBs. Natural frequencies and mode shapes give a good basis for checking the simulation models used in the design. Further development of the models to simulate the real behaviour of TTBs subjected to wind loads is needed.

For evaluating the dynamic properties of a structure, it is necessary to measure the response (for example accelerations) of the building to a varying force. The building response is normally measured using accelerometers. The force can be imparted to the structure using three principal approaches:

- Ambient vibration (AVT) – Excitation with unknown external force which is assumed to have a frequency spectrum which is broadly flat across the frequency range of interest.
- Free Vibration Test (FreeVT) – The structure is first set into motion by applying known initial conditions,

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e.g., by a pull followed by a sudden release or by some unmeasured artificial excitation, such as synchronized swaying of one or more humans or shaker, and then left to vibrate freely on its own.

- Forced vibration test (FVT) – excitation with a known force, for example from a shaker imparting an excitation force to the structure that can be measured, or an impact hammer instrumented with a force sensor.

These methods have benefits and drawbacks for measuring different dynamic properties and are suitable for establishing different properties. Depending on the property of interest, different test methods are most suited, see Table 2.

Table 2: *Dynamic properties and recommended method to use for evaluation.*

	Suitable testing methods		
Property of interest	AVT	FreeVT	FVT
Natural frequency	X	X	X
Modes shapes	X	X	X
Modal damping		X	X
Modal mass			X
Frequency response function			X

For measuring mode shapes, it is necessary to use several sensors along the height of the building. Strong amplitude-dependent behaviour is to be expected for TTBs. To address this in detail, dynamic testing techniques that can cope with such structural features, such as FVT or FreeVT, are required. Accelerometers must follow the motion of the TTB structure they are attached to. Timber floors in TTBs are often covered by acoustic layers. If horizontal shakers are used, such layers can prevent direct transmission of the shaker force to the TTB structure by introducing unwanted flexibility.

5 SUMMARY

This paper presents an overview of the most important results from the DynaTTB project. The results are gathered in a Guideline for engineers and researchers interested in designing and evaluating TTBs.

The results show that it is possible to measure the dynamic properties of the buildings. The results also show that to make an FE model that is valid in its representation of a building's dynamic behaviour in SLS, in terms of eigenfrequency and modes shapes, it is important to take the effect of stiffness in the connections, the foundation and in some cases also non-loadbearing structures such as partition walls, screeds and curtain walls into account.

The results also show that in most cases TTBs exhibit non-linear damping behaviour, which in some cases might be important to consider. In general, the damping is in the range of 1.5-3% of the critical viscous damping depending on the amplitude of the vibrations.

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7 REFERENCES

[1] ISO 10137, *Bases for design of structures – Serviceability of buildings and walkways against vibration*, no. Approved: 2008-03-17.

[2] EN 1991-1-4, *EN 1991-1-4 Eurocode 1: Actions on structures -Part 1-4: General actions -Wind actions*. 2005.

[3] A. Linderholt, P. Landel, and M. Johansson, "Forced response measurements on a seven storey timber building in Sweden," in *World Conference on Timber Engineering (WCTE 2023), Oslo 19-22 June*, 2023.

[4] B. Kurent, B. Brank, W. Kei Ao, A. Pavic, and M. Manthey, "On finite element modelling and model updating of multi-storey timber buildings," in *World Conference on Timber Engineering (WCTE 2023), Oslo 19-22 June*, 2023.

[5] K.-A. Malo, H. Stamatopoulos, F. Mikro Masaro, and S. Tulebekova, "Serviceability stiffness for timber connections with dowels and slotted-in steel plates," in *World Conference on Timber Engineering (WCTE 2023), Oslo 19-22 June*, 2023.

[6] 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.

[7] 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.

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

[9] 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.

[10] 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.

[11] O. Flamand and M. Manthey, "Wind shaking of high rise timber buildings," in *8th European African Conference on Wind Engineering (8EACWE), Bucharest, September 20-23*, 2022.

[12] O. Flamand and M. Manthey, "Improving the modelling of tall timber buildings," in *Current*

https://doi.org/10.52202/069179-0380

Perspectives and New Directions in Mechanics, Modelling and Design of Structural Systems, 2022.

[13] 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.

[14] 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.

[15] 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.

[16] W. K. Ao and A. Pavic, "Novel wirelessly synchronised modal testing of operational buildings using distributed OCXO high-precision data loggers," in *Proceedings of the 39th IMAC, A Conference and Exposition on Structural Dynamics 2021IMAC XXXIX* , 2021.

[17] Moelven, "Flervåningshus Trä8," 2022. https://www.moelven.com/se/produkter-och-tjanster/allt-om-limtra/flervaningshus-tra8/ (accessed Nov. 16, 2022).

[18] M. Green, *The case for Tall Wood Buildings*. 2012.

[19] E. Karacabeyli and C. Lum, *Technical Guide for the Design and Construction of Tall Wood Buildings in Canada Special Publication SP-543E*. 2022.

[20] Z. Chen, D. Tung, and E. Karacabeyli, *Modelling Guide for Timber Structures 2022-First Edition*. 2022.

[21] EN 1991-1-1, *Eurocode 1: Actions on structures - Part 1-1: General actions – Densities, self-weight, imposed loads for buildings*. Approved 2002-06-28.

[22] EN 1995-1-1, *Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings*, no. Approved 2004-12-10.
