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Gerhard Fink
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Holistic Design of Taller Timber Buildings



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Holistic Design of Taller Timber Buildings

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Contents

Introduction

COST Action HELEN – Holistic Design of Taller Timber Buildings	3
<i>Gerhard Fink, Robert Jockwer, Iztok Šušteršič, José Manuel Cabrero, Mislav Stepinac, Eleni Toumpanaki, Pedro Palma, Chiara Bedon, Daniele Casagrande, and Steffen Franke</i>	

Planning of Taller Timber Buildings - ULS and SLS design

Vertical Deformations in Tall Timber Buildings: Sources and In-Field Estimations	19
<i>Martina Sciomenta and Chiara Bedon</i>	
Design of Timber Columns of Tall Timber Buildings with Consideration of the Long-Term Behaviour	28
<i>Janusch Töpler and Jörg Schänzlin</i>	
Connections Design and Analysis: Numerical, Analytical and Code-Based Methods	36
<i>Martina Sciomenta and Chiara Bedon</i>	
High-Performance Connections	50
<i>Giacomo Iovane, Saeid Javidi, Beatrice Faggiano, Michele Mirra, Valentino Nicolussi, and Giuseppe D’Arenzo</i>	
Floor Design for Taller Timber Buildings	64
<i>Joonas Jaaranen, Sebastian Krug, Vlatka Rajcic, Martina Sciomenta, and Chiara Bedon</i>	
Vibration-Based Serviceability and Acoustic Assessment of Timber Floors	76
<i>Angelo Aloisio, Dag Pasquale Pasca, Thomas Hillberger, Roberto Tomasi, Thomas P. S. Reynolds, Chiara Bedon, Sven Vallely, Rok Prislán, Kemal Edip, Mohammadreza Salehi, Carlos Martín de la Concha Renedo, and Iván M. Díaz</i>	
Vibration-Based Structural Health Monitoring of Timber Structures	94
<i>Angelo Aloisio, Dag Pasquale Pasca, Pier Francesco Giordano, Marco Civera, Marco Martino Rosso, Maria Pina Limongelli, Thomas P. S. Reynolds, Chiara Bedon, and Blaž Kurent</i>	

Wind Design for Tall Timber Buildings	104
<i>Martina Sciomenta, Saule Tulebekova, and Haris Stamatopoulos</i>	
Vibration-Based Wind Design Provisions for Tall Timber Buildings	115
<i>Angelo Aloisio, Matiyas A. Bezabeh, Dag Pasquale Pasca, Marco Martino Rosso, Pier Francesco Giordano, Thomas Reynolds, Chiara Bedon, Kemal Haciefendioğlu, Saule Tulebekova, and Blaž Kurent</i>	
Performance of Taller Timber Buildings	
Moisture Management During Construction	127
<i>Matt Caldwell, Lucas Viereck, Patrik Aondio, and Nina Flexeder</i>	
Property Protection in the Event of a Fire	143
<i>Carl Pettersson, Leo Willem Menzemer, Petr Hejtmanek, and Daniel Brandon</i>	
Damage and Repair of Tall Timber Buildings	150
<i>Boris Forsthuber, Daniel Brandon, Eleni Toumpanaki, Jan Vcelak, and Luka Vojnovic</i>	
Lifecycle Impact Assessment for Tall Timber Building: Learning from HAUT	177
<i>Shady Attia</i>	
Estimation of Mechanical Properties and Assessment of Existing Timber Structures Using Non-Destructive Tools	186
<i>Patrick J. McGetrick, Roohollah M. Pirooz, David Gil-Moreno, Rimjhim Kashyap, and Conan O’Ceallaigh</i>	
How Long Can Timber Buildings Last? Strategies for Service Life and Sustainability	205
<i>Shady Attia, Tomasso Verdier, and Joris Van Acker</i>	
The New Model Building - A Research Initiative Piloting Post-Grenfell Holistic Design of Medium-Rise Residential Buildings in Timber	213
<i>Matt Caldwell</i>	
Hazard Criteria	
Structural Robustness: Design Framework for Enhanced Robustness	225
<i>Maria Felicita, Luka Vojnovic, Katharina Sroka, and Pedro Palma</i>	

Lateral-Load-Resisting Systems (LLRSs) in Taller Timber Buildings	238
<i>Michele Mirra, Giacomo Iovane, Beatrice Faggiano, Saeid Javidi, Victor Belafonte, Gabriele Tamagnone, Jorge Branco, Tuba Tatar, Wenchen Dong, and Giuseppe D'Arenzo</i>	
Seismic Protection Technologies	253
<i>Luka Naumovski, Onur Kaplan, Vojko Kilar, Erkan Çelebi, Giuseppe D'Arenzo, Beatrice Faggiano, Giacomo Iovane, Saeid Javidi, and Daniele Casagrande</i>	
Compartment Fire Dynamics in Taller Timber Buildings: Guidance for Performance-Based Fire Safety Engineering	272
<i>Ian Pope, Antonela Čolić, Chamith Karannagodage, Ahmed Ahmed Ali Awadallah, and Andrea Lucherini</i>	
Structural Fire Behaviour	288
<i>Felix Wiesner, Daniel Brandon, Andrea Lucherini, and Pedro Palma</i>	
Design of Timber Structures Subjected to Blast Loads	300
<i>Christian Viau, Aba Krouma, and Ghasan Doudak</i>	
Towards a Multi-hazard Framework for the Design of Taller Timber Structures	313
<i>Christian Viau, Onur Kaplan, Aba Krouma, Gabriele Tamagnone, Daniel Brandon, Felix Wiesner, Tuba Tatar, and Daniele Casagrande</i>	
 Circularity of Taller Timber Buildings	
Adaptability in Wood Construction: Barriers to Flexible Multi-Storey Timber Buildings	327
<i>E. A. K. J. Vandamme, M. Rinke, and R. N. Passarelli</i>	
An Investigation of Digital Infrastructure's Role in Repair and Reuse of Timber-Based Components in Taller Timber Buildings: An Interdisciplinary Case study of Digital Product Passport	335
<i>Katja Rodionova and Veikko Eeva</i>	
Disassembly and Reuse in Tall Timber Buildings: Advancing Circular Construction Practices	341
<i>José Manuel Cabrero, Lisa-Mareike Ottenhaus, Pedro Palma, and Shady Attia</i>	

Evaluating the Disassembly Potential of Timber Buildings: Development of Calculation Tool and Proof of Concept	350
<i>Lisa-Mareike Ottenhaus, Marta Hernández-Alda, Anna Davies, and José Manuel Cabrero</i>	
Design with Reclaimed Components in Timber Construction	355
<i>Kristina Kröll, Alec Singh, Aída Santana Sosa, Esther Vandamme, and Felipe Riola-Parada</i>	
Challenges and Potentials for Circulating Structural Timber and Engineered Wood Products	372
<i>Henri Ranttila, Gerhard Fink, Reinhard Brandner, and Daniel Ridley-Ellis</i>	
Circulation of Structural Timber: A Review of Opportunities and Challenges	377
<i>R. N. Passarelli, T. O. Chiletto, R. Brandner, and L. M. Ottenhaus</i>	
Special Aspects of Taller Timber Buildings	
Experimental and Numerical Investigations of Timber-Concrete Composite Slabs Subjected to Negative Bending Moments	383
<i>Sebastian Krug and Jörg Schänzlin</i>	
Experimentally Validated Bending Capacity Models for Strip-Reinforced Timber Beams	389
<i>Alex Sixie Cao, René Steiger, and Andrea Frangi</i>	
Deformation and Creep Recovery of Structural Timber Elements	393
<i>Conan O’Ceallaigh, Patrick J. McGetrick, Thomas Walsh, Gary Moran, Karol Sikora, Daniel McPolin, and Annette M. Harte</i>	
Creep Behaviour and Creep Recovery of FRP Reinforced Timber Elements	399
<i>Conan O’Ceallaigh, Patrick J. McGetrick, Thomas Walsh, Gary Moran, Karol Sikora, Daniel McPolin, and Annette M. Harte</i>	
Rate-Dependency and Hysteresis of Timber Connections with a Single Laterally-Loaded Dowel and a Slotted-in Steel Plate	403
<i>Katharina Sroka, Alex Sixie Cao, Pedro Palma, and Andrea Frangi</i>	

Fire Risk Perception of Timber Buildings: Implications
for the Responsibility of Designers 407
Leo Willem Menzemer

Author Index 413



Vibration-Based Wind Design Provisions for Tall Timber Buildings

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1 Introduction

It is well acknowledged that as the height of a building increases, wind forces tend to become the controlling design loads. In tall, slender and flexible structures, wind-induced vibration serviceability is more critical than in low-rise buildings, where strength is usually the governing design criterion. Using engineered timber panels, tall mass timber buildings have reached heights comparable to those of mid-rise concrete and steel buildings. Therefore, wind-induced vibration needs attention even in mid-rise buildings when timber is used as a structural material for lateral load resistance. It has been shown that in timber buildings as low as seven stories wind-induced vibrations can be a governing design criterion [1]. Due to the relatively high strength-to-weight ratio of wood, timber buildings tend to be lighter and more flexible compared to their reinforced concrete counterparts. Typically, timber structures possess one-third the stiffness of concrete buildings and weigh one-fourth as much. This, in turn, means that they are more prone to

wind-induced vibrations that might cause discomfort to the occupants. Excessive wind-induced vibrations impair their long-term safety and functionality, which lowers their market value and may have an impact on the comfort and health of occupants. For these reasons, serviceability issues related to wind-induced vibration are considered a hindering factor for the design of tall timber buildings.

Compared to the ultimate limit states that define collapse or other forms of catastrophic failure of the structures, serviceability limit states define a loss of comfort or functional performance of the building. They establish a level of quality of the building and are often negotiated by the investor and the contractor to meet the expected functionality of the building. Its limitation may be set by the occupants' perception or technical requirements of the installed building elements or machines. Since serviceability limit states are not directly related to safety, professional committees and code bodies seem reluctant to codify serviceability issues rigidly. This reluctance is probably due to the different opinions on the purpose of building codes: protection for life safety or the establishment of complete minimum design standards. However, the fact that serviceability limit states are usually not codified should not diminish their importance. While safety is usually not an issue in this topic, the economic consequences can be substantial, especially when they are a part of contractual requirements set by the investors.

Whereas the research on the seismic response of timber buildings has progressed at a high pace, wind performance of mid and high-rise timber buildings has been studied more scarcely. There is no specific reported cases on wind-related human discomfort in tall timber buildings, mainly because there is no significant sample of such buildings for a meaningful statistical evaluation. Therefore, the wind modelling and the comfort criteria originate from past studies on other structural systems, see [2]. However, the lack of specific studies on timber buildings does not affect comfort criteria limits, which depend on the interaction between human perception and building dynamics and are not directly related to the building material.

2 Vibration Response Analysis Under Wind Excitation

Comfort criteria are based on the human perception of vibration, which is, due to substantial variation in individual physiological and psychological responses, very difficult to quantify. It is not fully understood how different quantities of motion (such as displacement, velocity, acceleration, and their derivatives) contribute to the perception of motion, however, the current comfort criteria are assessed through acceleration curves. These base curves represent either the threshold of perception of motion of some percentage of people or the limit for probable adverse comments by the occupants [3,4]. They depend on the vibration frequency of the structural system and the orientation of the vibration relative to the human body axes. Firstly, a performance indicator (e.g. running root-mean-square, peak acceleration) is computed based on the building's properties and

the assumed wind loads. This indicator is then compared to the base perception curves to evaluate the system's performance. Some of the most relevant standards containing serviceability criteria related to motion perception of the occupants are hereby listed and reported in Fig. 1:

- ISO 10137 (2007) [3]. The standard recommends the serviceability criteria against the building's vibrations. Annex D provides a method for evaluating the human perception of wind-induced motions in buildings, giving acceptable limits in terms of peak acceleration, at the natural frequency, in the principal direction (along-wind, cross-wind, torsion) of the building. The peak acceleration should be calculated for wind speed with a one-year return period. The criteria is based on assuming $\text{peak} = 3.5 \cdot \text{RMS}$
- ISO 6897 (1984) [4]. The standard, based on [5], covers building, whose frequency is 0.063 Hz-1 Hz, gives limit values of root mean square (RMS) accelerations for buildings used for general purposes. The limits are based on the wind levels with a five-year return period.
- AIJ (2004) [6]. The Japanese guidelines provide five curves: H-10, H-30, H-50, H-70 and H-90, where the number of each curve indicates the perception probability, expressed as a percentage of people who can perceive the given vibration level. The guidelines recommend no specific limit, which is to be decided by the owner and the designer.
- RWDI/BLWTL industry criterion [7]. A widely used industry practice, especially in North America, limits the 10-year return period peak acceleration to below 18 milli-g. While not formalized in a standard, this criterion is often adopted in practice.

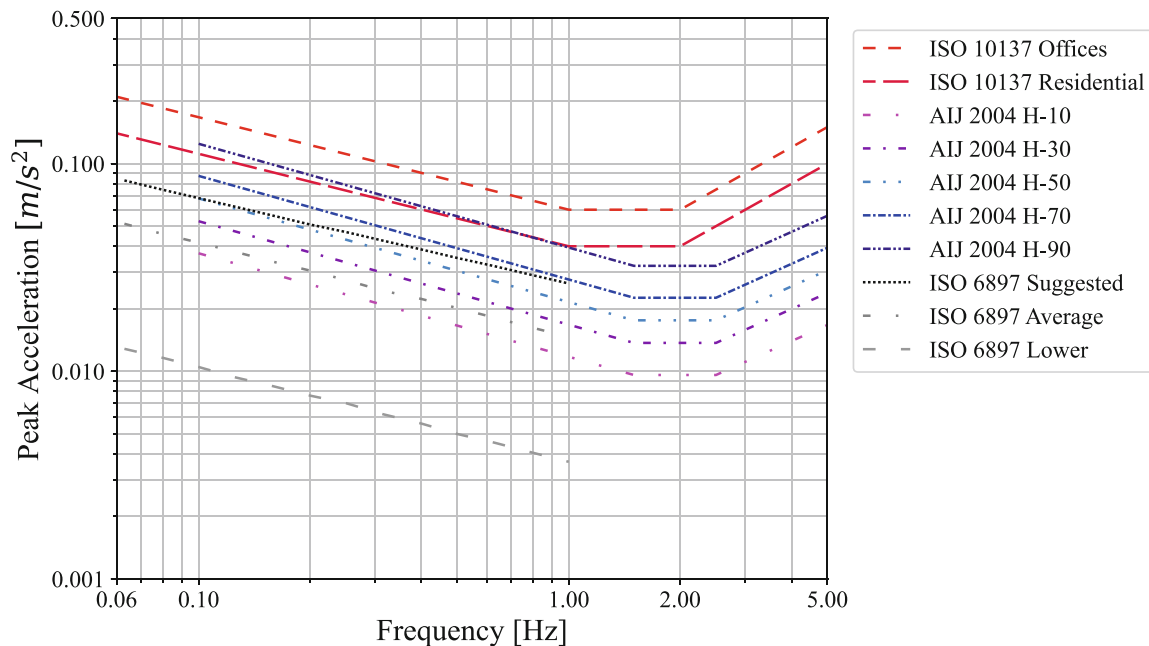


Fig. 1. Comparison between different perception curves (RMS values from ISO 6897 are multiplied by 3.5 to be comparable with peak acceleration limits).

The dynamic response of tall buildings to a wind load is a complex phenomenon, as the wind significantly varies in velocity and direction over time and space. To achieve simplification, building codes treat wind loads as quasi-static loads. The gust effect is also included as a turbulence factor added to the quasi-static component for high slender structures. Furthermore, the effect of the wind on a building will be affected by its exposure, the roughness of the terrain around it as well as the shape and height of the building. The gust load factor approach originates from the work of Davenport [8] and is a simplified frequency-domain method in which the wind load's standard deviation and the dynamic response's amplitude are multiplied by a peak factor to obtain the peak response. The standard deviation of the response and a peak factor are obtained based on random vibrations theory. Because of its simplicity, the gust factor method has received widespread acceptance worldwide and is employed in wind loading codes and standards in almost all major countries. According to the method in Annex B of EN 1991-1-4, for instance, the characteristic wind-induced acceleration, in the along-wind direction, for a point at height z , is calculated as:

$$a_{\text{peak}}(z) = K_p b_b h_b q_{z,\text{ref}} c_{fw} K \Phi_{1,x}(z) \frac{1}{M_1} R \quad (1)$$

$a_{\text{peak}}(z)$ Peak acceleration response (m/s²) at height z

K_p Peak factor

b_b Building width

h_b Building height

$q_{z,\text{ref}}$ Reference wind load (N/m²) at height z_{ref}

c_{fw} Force coefficient

K Dimensionless coefficient that scales turbulence effects

$\Phi_{1,x}(z)$ First-mode shape in the wind (cross-wind) direction, evaluated at height z

M_1 Modal mass of the first mode

R Resonance response factor

The peak response obtained can then be compared with peak acceleration criteria, such as ISO 10137 [9]. However, the response of buildings subjected to wind loads can be estimated more precisely with time-domain analysis using in-situ wind measurements or wind tunnel experiments, but also with methods combining spectral analysis and time-domain analysis [10–12]. The wind is described in a frequency-domain wind spectrum, and then a time series is generated from the spectrum. The dynamic response of the structure can be computed through numerical integration of the modal equation of motion. It should be mentioned that wind tunnel testing is recommended for mass-timber structures that are more than 20 stories tall, flexible, and have complex shapes, and are subject to wake buffeting from upwind buildings or channelling effects, and are susceptible to aeroelastic phenomena.

For calculating acceleration according to EN 1991-1-4 and checking it against the base curves, estimation of the natural frequency is necessary. Annex F of EN 1991-1-4 offers a simplified empirical equation for the fundamental frequency in Hertz

$$f_1 = 46/h \quad (2)$$

where h is the height of the building in meters. This equation can give a quick rough estimate, however, it can not be used for improving the design of the building, since the only variable is the height of the building. Reynolds et al. [13] compare the equation to ambient vibration test results for eleven multi-storey timber buildings in Europe, and find that it is a reasonable predictor of the fundamental frequency, although $f_1 = 55/h$ is a better fit to the measured data.

Designers of mid- and high-rise timber buildings often develop FE models to estimate their modal properties. Several research works have been carried out to find better modelling techniques for accurate estimation of modal properties of timber buildings (e.g. [14–19]). The main findings are that the nonstructural elements (such as façade, partition walls, plasterboards) can significantly increase the stiffness of the building (although this may not outweigh the effect of their added mass on the fundamental frequency) and that the type of construction (platform frame or balloon frame) importantly defines the stiffness properties of the building. The research is yet inconclusive about the influence of the connections in CLT buildings, however, it seems that soundproofing bedding under cross-laminated walls is an important factor in determining the stiffness of the connections. In glulam frame buildings, the stiffness and damping of the glulam connections can influence the modal properties [17,20]. It is important to note that modal properties of timber buildings vary seasonally, mainly due to environmental factors such as moisture content [21].

Most of the research work carried out during recent years deals with numerical studies where different structural systems (e.g. post-and-beams, CLT, etc.) are analysed throughout case studies and parametric analyses [12,22–32]. Specifically, Johansson et al. [22] studied the response of two archetypes (i.e. CLT buildings, glulam post-and-beam with a concrete shaft) to wind-induced acceleration according to EN 1991-1-4 and compared the results of the simplified analytical calculations with the limits of ISO 10137. They extended the analysis to a 48 m (16 storeys) high building where they studied the effect of doubling and tripling the mass, stiffness and damping ratio. In [23], the authors analysed 22-storey structures having an internal CLT core and a post-and-beam structure at the perimeter. They modelled the structure with FE software to get more reliable results regarding natural frequencies and mode shapes. Edskär and Lindelöw [24] performed a parametric analysis on the FE model of a CLT structure varying the footprint, height, damping ratio, wall stiffness, wall density and additional surface loads and studied the influence of these parameters on the dynamic response of the building. In [25], the authors extended the parametric analyses to a post and beam type of structure and compare it to the response of a

CLT one. In the same direction, Zhao et al. [26, 27] performed parametric studies on the peak accelerations of CLT and glulam frames buildings, respectively. The structures were assumed to be located in Glasgow and have 30 storeys. Furthermore, the varied parameters were the timber material properties and building masses. In these papers, the accelerations were also calculated according to the Eurocodes, and the response is evaluated concerning ISO 10137 limits. Landel et al. [28] compared four procedures to evaluate the along wind accelerations on four existing tall timber buildings, highlighting high variations between the different codes. Cao and Stamatopoulos [12] delivered a numerical investigation on the response of moment-resisting frames subject to wind loads. They performed over one million simulations on planar frames where several parameters (e.g. floor height, floor number, beam stiffness) were varied. The response of the planar frames was evaluated with the simplified gust approach, but also performing time-domain analyses explicitly considering the time series of the wind force. A quite interesting finding was that the gust factor approach might underestimate the response for frames with up to 10–12 floors while overestimating the accelerations for frames with more than 10–12 storeys [12]. Bezabeh et al. [29] examined the dynamic response and serviceability performance of five case study tall mass-timber buildings varying in height (10-, 15-, 20-, 30-, and 40-story). Bezabeh et al. [10, 11] proposed a probabilistic procedure to assess the serviceability performance of tall mass-timber buildings, applying the complete framework to a case study consisting of a 102-m tall building. The framework incorporated uncertainties at each step of the wind-loading chain. The design process consisted of a preliminary strength design using building code provisions. Then serviceability checks were performed using wind loads obtained from aerodynamic wind tunnel tests. Finally, the detailed probabilistic performance assessment was performed with structural reliability analysis using Monte Carlo sampling to propagate the uncertainties through the wind loading chain. The results from reliability analysis were used to develop fragility curves for wind vulnerability estimations. Lazzarini et al. [30] studied the comfort assessment of the 18-storey “Mjøstårnet” building in Norway, applying computational fluid dynamic (CFD) analyses to simulate the wind flow around the building. The results of the CFD analysis are then used to extrapolate detailed pressure data, which is applied to a generalized model and a reduced model to obtain accurate evaluations of wind-induced motions. Wind-induced vibrations in the across-wind directions were particularly strong, which is not captured by the current standard, indicating the importance of applying fluid dynamic analyses. Kurent et al. [1] performed a serviceability check of two timber and one hybrid timber-concrete buildings and showed that checking only the first mode of vibration is not enough, since the second mode can sometimes be more critical.

3 Conclusions

Wind-induced vibration governs the serviceability design of mid-and high-rise timber buildings at lower heights than it does for comparable concrete structures because the high strength-to-weight ratio of wood leads to lower mass and greater flexibility. Although comfort criteria such as ISO 10137, ISO 6897 and the AIJ guidelines are material-agnostic, their verification still hinges on an accurate prediction of peak accelerations; the review presented here shows that the traditional gust factor approach embedded in EN 1991-1-4 can be adequate only when its inputs, the first two natural frequencies, modal masses and damping ratios, are themselves reliable. Empirical height-frequency formulas (e.g. $f_1 = 46/h$) have yet to be validated for timber and therefore carry large uncertainty, while finite-element predictions remain sensitive to the stiffness contribution of non-structural components, connection bedding and seasonal moisture variation. Case-study simulations confirm that doubling mass or stiffness can halve the peak acceleration, but also reveal that higher modes, particularly the second bending mode, may control comfort more than the fundamental one [1]. Parametric studies further indicate that the gust-factor method may underestimate accelerations for 10- to 12-storey frames and overestimate them for taller systems, suggesting that time-domain analyses or hybrid spectral/time techniques should become routine for slender timber towers [12]. The scarcity of full-scale monitoring data remains the principal obstacle to refining both simplified and sophisticated models; without such data it is impossible to quantify the true damping achievable through façade friction, interior fit-out or supplemental devices, or to calibrate probabilistic fragility curves that capture the combined effect of wind variability and modelling uncertainty.

In practical terms, designers should (i) develop FE models that include sheathing, partitions and realistic connection stiffness, (ii) evaluate at least the first two lateral modes in both along- and cross-wind directions, (iii) supplement code-based gust calculations with time-domain checks when predicted peak accelerations approach 80% of the relevant perception limits, iv) consider wind tunnel testing for mass-timber buildings that are more than 20 stories tall, flexible, and have complex shapes, and are subject to wake buffeting from upwind buildings or channelling effects, and are susceptible to aeroelastic phenomena, and (iv) consider tuned mass or viscous dampers early in the design when mass or stiffness increases conflict with sustainability targets. On the research side, priority should be given to long-term dynamic monitoring of completed mass-timber towers coupled with in-situ wind measurements, to wind-tunnel databases that cover the distinctive geometries of timber bracing and cores, and to probabilistic frameworks that propagate material, connection, and environmental uncertainties through to serviceability risk metrics.

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References

1. Kurent, B., Friedman, N., Brank, B.: Modelling of multi-storey cross-laminated timber buildings for vibration serviceability. *Buildings* **14**, 689 (2024)
2. Lamb, S., Kwok, K.C., Walton, D.: A longitudinal field study of the effects of wind-induced building motion on occupant wellbeing and work performance. *J. Wind Eng. Ind. Aerodyn.* **133**, 39–51 (2014)
3. I. O. for Standardization, Bases for Design of Structures—serviceability of Buildings and Walkways Against Vibrations. ISO (2007)
4. I. 6897, Guidelines for the evaluation of the response of occupants of fixed structures, especially buildings and off-shore structures, to low-frequency horizontal motion (0.063 to 1hz) (1984)
5. Irwin, A.: Perception, comfort and performance criteria for human beings exposed to whole body pure yaw vibration and vibration containing yaw and translational components. *J. Sound Vib.* **76**(4), 481–497 (1981)
6. Aij, A.: Guidelines for the evaluation of habitability to building vibration, AIJ (2004)
7. RWDI, Structural performance: wind-induced motion of tall buildings (2017). RWDI Fact Sheet
8. Davenport, A.: How can we simplify and generalize wind loads? *J. Wind Eng. Ind. Aerodyn.* **54**, 657–669 (1995)
9. Kareem, A.: Synthesis of fluctuating along wind loads on buildings. *J. Eng. Mech.* **112**(1), 121–125 (1986)
10. Bezabeh, M., Bitsuamlak, G., Popovski, M., Tesfamariam, S.: Probabilistic serviceability-performance assessment of tall mass-timber buildings subjected to stochastic wind loads: Part i - structural design and wind tunnel testing. *J. Wind Eng. Ind. Aerodyn.* **181**, 85–103 (2018)
11. Bezabeh, M., Bitsuamlak, G., Popovski, M., Tesfamariam, S.: Probabilistic serviceability-performance assessment of tall mass-timber buildings subjected to stochastic wind loads: Part ii - structural reliability analysis. *J. Wind Eng. Ind. Aerodyn.* **181**, 112–125 (2018)
12. Cao, A., Stamatopoulos, H.: A theoretical study of the dynamic response of planar timber frames with semi-rigid moment-resisting connections subjected to wind loads, *Engineering Structures*, vol. 240 (2021)
13. Reynolds, T., Feldmann, A., Ramage, M., Chang, W., Harris, R., Dietsch, P.: Design parameters for lateral vibration of multi-storey timber buildings. In: *International Network on Timber Engineering Research Proceedings (INTER 2016)* (2016)
14. Kurent, B., Brank, B., Ao, W.: Model updating of seven-storey cross-laminated timber building designed on frequency-response-functions-based modal testing, *Structure and Infrastructure Engineering*, vol. 19, no. 2, pp. 178–196, (2023). cited By 12
15. Kurent, B., Friedman, N., Aloisio, A., Pasca, D.P., Tomasi, R., Brank, B.: Bayesian model updating of eight-storey CLT building using modal data. *Probab. Eng. Mech.* **19**(2), 178–196 (2024)
16. Kurent, B., Ao, W.K., Pavic, A., Pérez, F., Brank, B.: Modal testing and finite element model updating of full-scale hybrid timber-concrete building. *Eng. Struct.* **289**, 116250 (2023)
17. Tulebekova, S., Malo, K., RÃ, nnquist, A., NÃvik, P.: Modeling stiffness of connections and non-structural elements for dynamic response of taller glulam timber frame buildings, *Engineering Structures*, vol. 261 (2022)

18. Tulebekova, S., Malo, K.A., Rønnquist, A.: Dynamic identification and model calibration of connection stiffness in multi-storey cross-laminated timber buildings. *J. Build. Eng.* **72**, 106607 (2023)
19. Reynolds, T., Harris, R., Chang, W.-S., Bregulla, J., Bawcombe, J.: Ambient vibration tests of a cross-laminated timber building. *Proc. Inst. Civil Eng. Constr. Mater.* **168**(3), 121–131 (2015)
20. Tulebekova, S., Stamatopoulos, S., Malo, K.: A framework for the estimation of damping ratio of glued—laminated buildings by use of analysis in the time domain, *Materials*, vol. 18 (2025)
21. Larsson, C., Abdeljaber, O., Bolmsvik, Dorn, M.: Long-term analysis of the environmental effects on the global dynamic properties of a hybrid timber-concrete building, *Engineering Structures*, vol. 268 (2022)
22. Johansson, M., Linderholt, A., Bolmsvik, Å., Jarnerö, K., Olsson, J., Reynolds, T.: Building higher with light-weight timber structures—the effect of wind induced vibrations. In: 44th International Congress and Exposition on Noise Control Engineering, INTER-NOISE 2015 (2015)
23. Johansson, M., Linderholt, A., Jarnerö, K., Landel, P.: Tall timber buildings—a preliminary study of wind-induced vibrations of a 22-storey building, *Proceedings of the WCTE* (2016)
24. Edskar, I., Lidelow, H.: Wind-induced vibrations in timber buildings—parameter study of cross-laminated timber residential structures. *Struct. Eng. Int.* **27**(2), 205–216 (2017)
25. Edskär, I., Lidelöw, H.: Dynamic properties of cross-laminated timber and timber truss building systems. *Eng. Struct.* **186**, 525–535 (2019)
26. Zhao, X., Zhang, B., Kilpatrick, T., Sanderson, I.: Numerical analysis on global serviceability behaviours of tall clt buildings to the eurocodes and uk national annexes, *Buildings*, **11**(3) (2021)
27. Zhao, X., Zhang, B., Kilpatrick, T., Sanderson, I., Liu, D.: Numerical analysis on global serviceability behaviours of tall glulam frame buildings to the Eurocodes and UK national annexes. *Journal of Civil Engineering and Construction* **10**(3), 109–122 (2021)
28. Landel, P., Johansson, M., Linderholt, A.: “Comparative study of wind-induced accelerations in tall timber buildings according to four methods. In: WCTE 2021, World Conference on Timber Engineering, Santiago, Chile, 9-12 August (2021)
29. Bezabeh, M., Bitsuamlak, G., Popovski, M., Tesfamariam, S.: Dynamic response of tall mass-timber buildings to wind excitation. *J. Struct. Eng. (United States)* **146**(10) (2020)
30. Lazzarini, E., Frison, G., Trutalli, D., Marchi, L., Scotta, R.: Comfort assessment of high-rise timber buildings exposed to wind-induced vibrations, *Struct. Design Tall Special Build.* **30**(12) (2021)
31. Ussher, E., Aloisio, A., Rathy, S.: Effect of lateral resisting systems on the wind-induced serviceability response of tall timber buildings. *Case Stud. Constr. Mater.* **19**, e02540 (2023)
32. Reynolds, T., Casagrande, D., Tomasi, R.: Comparison of multi-storey cross-laminated timber and timber frame buildings by in situ modal analysis. *Constr. Build. Mater.* **102**, 1009–1017 (2016)

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