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Recorded natural frequencies of timber buildings – A review

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ABSTRACT: The structural design of multi-story timber buildings is often governed by serviceability criteria limiting wind-induced vibration. To perform a serviceability check, the natural frequencies of the building need to be estimated, for which empirical equations are proposed by building codes. Their accuracy is not validated for timber buildings. This paper is a review of measured natural frequencies of 25 timber and hybrid timber buildings of heights between 16 m and 85 m. The natural frequencies and building heights are used for validating the empirical equations. The considered empirical equations are from the Eurocode, the American, Canadian, Japanese, and Italian building codes.

KEYWORDS: multi-story timber buildings, natural frequency, modal analysis, wind-induced vibration, serviceability

1 – INTRODUCTION

One of the primary considerations in the design of high-rise buildings is wind-induced vibrations. They play an even more significant role in timber buildings due to their lightweight designs. Satisfying vibration serviceability criteria is often a governing design criterion, even for buildings as low as seven stories [1]. Typically, one of two ISO standards is adopted for serviceability checking. ISO 10137 [2] restricts 1-year peak accelerations while ISO 6897 [3] adopts 5-year root–mean–square horizontal accelerations as a criterion. The limit curves of both standards are frequency-dependent, which necessitates the estimation of the natural frequencies of the building. Furthermore, the calculation of peak or root-mean-square accelerations by different codes also requires information about the building's natural frequency, as well as to determine the structural factor for wind load calculations of tall and slender buildings according to codes such as the Eurocode. They may be estimated by finite element modeling. However, it is time-consuming, and while some guidelines for modeling exist [1], they lack precise instruction for consideration of non-structural elements and connections between timber elements. On the other hand, building codes offer simplified empirical equations based on the height of the building, which may provide at least a rough estimation. Nevertheless, they have not yet been validated for timber buildings.

In 2016, Reynolds et al. [4] made a state-of-the-art review of the 11 then-built tallest timber buildings, ranging in construction height between 10 m and 49 m. Since then, the construction of tall timber buildings has significantly increased, where the current tallest timber buildings exceed the height of 80 m [5]. The following paper presents an updated review of measured natural frequencies of 25 timber and hybrid timber buildings and validates the empirical equations of several building codes. In addition, a new empirical equation is proposed based on the data of the 25 analyzed buildings.

2 – BACKGROUND

This paper reviews the field tests of 25 timber buildings of heights between 16 m to 85 m. The data about the buildings, such as the height, fundamental natural frequency, and a short description of the structural system, are collected in Table 1. The height of the building was defined as the architectural height according to the Council on Tall Buildings and Urban Habitat [5]. In case the choice was ambiguous, the description is included in the notes of Table 1. The buildings are differentiated by their structural design into the following four classes: light-frame timber (LFT), cross-laminated timber (CLT), glued-laminated timber (GLT), and hybrid timber buildings. The different classes are visualized in Figure 1.

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Table 1: Information about the timber and hybrid timber buildings included in this study. Three of the buildings have been measured by the authors and the results have not yet been published. These studies are denoted in the column 'Ref.' as NP.

#	Type	Name	Location	Stories	Height	1st freq.	Ref.	Note
1	LFT	Pilgatan	Varberg, SE	6	19 m	2.74 Hz	[6]	Prefabricated LFT elements are used.
2	CLT	Trinity	Cambridge, UK	5	16 m	4.48 Hz	[7]	The bottom story is in concrete.
3	CLT	University of East Anglia	Norwich, UK	7	21 m	2.45 Hz	[8]	The whole above-ground structure is in CLT.
4	CLT	Yoker	Glasgow, UK	7	22 m	2.85 Hz	[9]	The whole above-ground structure is in CLT.
5	CLT	Skymningen	Växjö, SE	6	25 m	2.43 Hz	NP	The bottom story is in concrete.
6	CLT	Palisaden	Ås, NO	8	27 m	1.88 Hz	[10]	The whole above-ground structure is in CLT.
7	CLT	Limnologen	Växjö, SE	8	27 m	2.24 Hz	[8]	The bottom story is in concrete.
8	CLT	Moholt	Trondheim, NO	9	28 m	1.98 Hz	[11]	The bottom story is in concrete.
9	CLT	Biologen	Växjö, SE	9	28 m	2.58 Hz	[12]	The bottom two stories are in concrete. The CLT structure above extends from 3 to 7 stories. The height ranges from 16 m to 28 m.
10	CLT	Stadthaus	London, UK	9	29 m	2.26 Hz	[8]	The bottom story is in concrete.
11	CLT	Dramsvegen Panorama	Tromsø, NO	10	30 m	2.15 Hz	[11]	The bottom three stories are in concrete.
12	CLT	Dramsvegen Panorama	Tromsø, NO	13	39 m	1.30 Hz	[11]	The bottom two stories are in concrete
13	CLT	Cederhusen	Stockholm, SE	13	43 m	1.38 Hz	[13]	The bottom two stories are in concrete.
14	GLT	Eken	Mariestad, SE	7	24 m	2.40 Hz	[14]	A half of the bottom story is in concrete. The rest of the structure (the columns, beams, and bracings) are made of GLT. For slabs, the prefabricated timber frame system was used. The ridge of the roof was considered to be the top of the building.
15	GLT	Treet	Bergen, NO	14	51 m	0.975	[15]	Slabs of stories 5 and 10, as well as roof slabs, are in concrete. Prefabricated volumetric building modules are stacked up on top of each other by up to 4 stories. They are supported by the main GLT structure.
16	GLT	Fyrtornet	Malmö, SE	11	51 m	1.14 Hz	NP	The main load-bearing structural system of the building is the post-and-beam system with GLT bracing. The building also features a CLT elevator and stair shaft. The floor slabs are made of CLT, and the roof slab is concrete.
17	GLT	Mjøstårnet	Brumunddal, NO	18	85 m	0.49 Hz	[16]	The top seven slabs are in concrete. Height is measured up to the top of the timber truss structure. The height measured to the top roof slab is 74 m.
18	Hybrid	N/A	Trento, IT	5	16 m	4.13 Hz	[17]	The building features LFT walls, timber-concrete composite slabs, and a concrete core. It has the same floor layout as building 20.
19	Hybrid	N/A	Trento, IT	5	16 m	4.06 Hz	[17]	CLT is used for the walls and slabs. The building features a concrete core. It has the same floor layout as building 19.
20	Hybrid	Charlie	Växjö, SE	4	17 m	3.21 Hz	[18]	The building features a GLT post and beam system, CLT slabs, steel bracing, and two concrete cores.
21	Hybrid	TreedIt	Paris, FR	12	36 m	1.39 Hz	[19]	The bottom story is in concrete. The building features a GLT post and beam system, concrete core, and concrete slabs.
22	Hybrid	Brock Commons	Vancouver, CA	18	54 m	0.94 Hz	[20]	The bottom story is in concrete. The building features GLT columns, CLT slabs, and two concrete cores.
23	Hybrid	Hyperion	Bordeaux, FR	16	56 m	0.95 Hz	[21]	The first three stories are in concrete. The building features steel columns, GLT beams, CLT slabs, and a concrete core.
24	Hybrid	Haut	Amsterdam, NL	21	73 m	0.71 Hz	[22]	The bottom two stories are in concrete. The building features a concrete core, CLT walls, concrete beams, and timber-concrete composite slabs.
25	Hybrid	HoHo Tower	Vienna, AT	24	84 m	0.94 Hz	NP	The bottom story is in concrete. The building features a massive concrete core, GLT columns, and timber-concrete composite slabs.

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a) b) c) d)

Figure 1. Visualization of different types of timber structures where a) shows an LFT structure, b) a CLT structure, c) a GLT-framed structure, and d) a hybrid structure.

2.1 LFT buildings

LFT buildings are characterized by the use of regular timber studs for LFT walls and slabs, complemented by shear plates nailed on the studs. These shear plates are usually oriented strand boards (OSB), plywood plates, or gypsum plates, which give the element lateral stability. Two such buildings are included in the study. The construction type is very common in one or two-story residential buildings, although there are several examples of this type used in residential buildings up to six stories. The analysis includes one such multi-story building with a height of 19 m.

2.2 CLT buildings

The most frequent building system within the measured buildings is CLT, with twelve buildings. CLT buildings are characterized by a structural system that uses CLT elements, both as structural walls and structural slabs. Commonly, these buildings have one or two stories acting as a concrete podium. Despite the use of concrete in the bottom stories (or stories), the buildings are not considered a hybrid since the majority of the height is achieved by the timber elements. The height of the building includes concrete stories in the calculations. A small percentage of structural elements of different materials are allowed to still be considered a CLT building. The tallest building in this group is Cederhusen, which is 43 m in height.

2.3 GLT-framed buildings

The GLT buildings consist of post and beam truss systems, including GLT bracing elements. For the floor slabs, CLT panels or prefabricated timber frame slabs may be used. In this group, concrete podiums were less common. Only in one of the buildings, half the bottom story was in concrete. The GLT-framed building group, with four observed buildings, was less represented than the CLT group. However, they achieved greater heights, with the three buildings being taller than 50 m and the tallest being Mjøstårnet, with a height of 85 m. Some buildings featured one or more concrete slabs, either for achieving serviceability criteria or for structural reasons.

2.4 Hybrid buildings

The group of hybrid buildings is more versatile. The main criterion for including buildings in this group is that at least one other structural material than timber is used throughout the height of the building in significant proportion. These elements should contribute to the lateral stability of the building. All eight buildings of that group included one or more concrete cores, while some also included concrete or steel columns and bracing elements. Timber-concrete composite floors are commonly used in this group. Greater heights are achieved in this group where four buildings exceed 50 m, and the tallest is HoHo Tower with 84 m.

3 – NATURAL FREQUENCY ESTIMATION APPROACHES

Some building codes offer simplified equations for determining the fundamental natural frequency of the building as a part of wind or seismic dynamic analysis. Commonly, more than one equation is proposed to account for different structural systems. The equations provided by five building codes (current or former) are presented in Table 2. They use the building height as the basis for calculating the fundamental natural frequency.

The Eurocode 1 (EC) [23] in the part for calculating the wind actions offers one equation for buildings of any structural material that is taller than 50 m.

The American Building Code (ASCE) [24] provides four different equations to calculate the fundamental natural frequency of buildings with a height of less than 91 meters and less than four times its effective length (in the direction of the wind). Three of those are empirical equations expressed as the function of the height of the building and are included in this study.

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Table 2: Empirical equations for estimating the fundamental natural frequency of a building proposed by various building codes.

Code	Equation	Note
EC	$46/h$	Taller than 50 m.
ASCE 7-22	$8.58/h^{0.8}$	Steel moment-resisting frame building.
	$14.93/h^{0.9}$	Concrete moment-resisting frame building.
	$22.86/h$	Steel or concrete buildings with other lateral-force-resisting systems
NBCC 2015	$20/h^{0.75}$	Building using bracings.
	$40/h$	Building using shear walls.
AIJ	$67/h$	Concrete buildings.
	$50/h$	Steel buildings.
NTC 2008	$11.76/h^{0.75}$	Steel buildings up to 40 m.
	$13.33/h^{0.75}$	Concrete buildings up to 40 m.
	$20/h^{0.75}$	Other buildings up to 40 m.

The National Building Code of Canada (NBCC) [25] proposes in its structural commentary two equations for estimating the lateral time period for the purpose of seismic analysis. One is used for buildings with bracings and the second with shear walls. The equations are inverted to express the computation of the natural frequency.

The Architectural Institute of Japan (AIJ) [26] in the Recommendations for loads on buildings proposes two equations, one for concrete and one for steel buildings.

Finally, the Italian Technical construction norm (NTC) from 2008 [27] provides the estimation of the time period for three types of buildings (steel, concrete, and other types of buildings). The NTC states that the equations are applicable only to buildings of heights up to 40 m.

None of the building codes explicitly consider a specific equation for timber buildings. For this reason, all presented equations are tested on the selected set of 25 timber and hybrid timber buildings.

4 – RESULTS

The collected information on building heights and the fundamental natural frequencies, given in Table 1, is visualized together with the considered empirical equations in Figure 2.

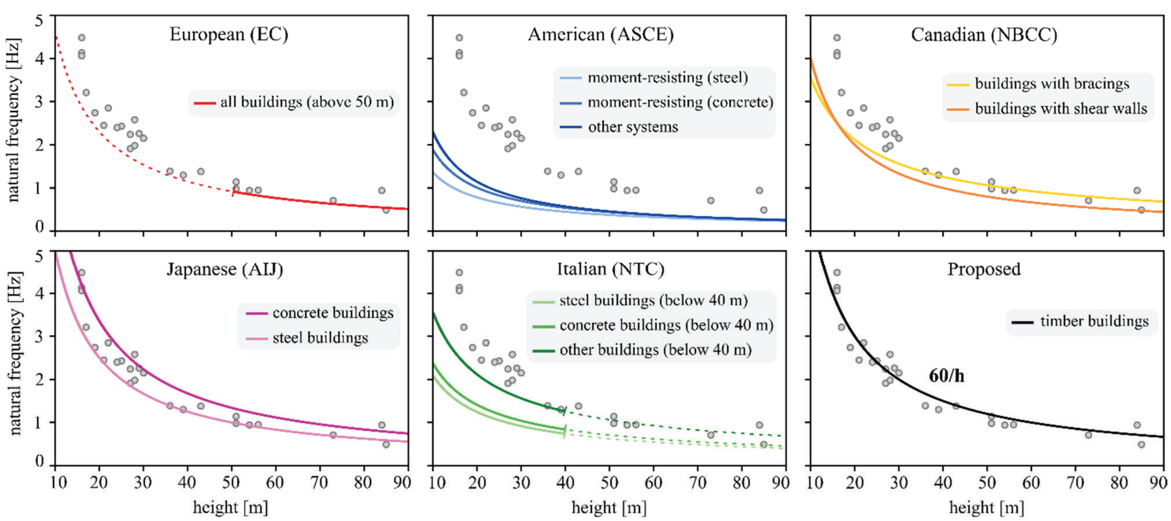

Figure 2: The validation of the building codes and the proposed empirical equation against the data of the heights and measured natural frequencies of 25 analyzed timber buildings.

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It can be observed that all equations given by ASCE largely underestimate the frequency for all considered buildings. The Italian NTC also underestimates the frequency with the empirical equations for steel and concrete buildings. The equation proposed by NTC for buildings with other materials makes a better estimation. The same equation is used by the Canadian NBCC for buildings with bracings.

It can be observed that the shape of the functions of the form C/h fits better to the analyzed dataset than those of the form C/h^{α}. Of the equations assuming inverse proportionality between the fundamental frequency and the height of the building, EC and AIJ make the most accurate estimations.

Additionally, the dataset is used to find a better empirical equation suitable for timber and hybrid timber buildings. An inverse proportionality is assumed in the form of $f_1 = C/h$, where a constant C should be found such that the coefficient of determination R^2 is maximized. By rounding the value to the closest integer, the following empirical equation is obtained

$$f_1 = \frac{60}{h},$$

where f_1 is the fundamental natural frequency in Hertz and h the height of the building in meters. The empirical equation yields the coefficient of determination $R^2 = 0.93$.

The proportionality between the fundamental frequency and the inverse of the height is shown in Figure 3. Within 25 of the analyzed buildings, 20 are captured between $50/h$ and $70/h$. Each of the five buildings that fall out of these bounds has a specific feature that explains the deviation from the average. Building 2 has a self-supported masonry wall for the façade that is laterally connected to the CLT structure, thus increasing the stiffness. Building 9 has a distinct V shape with nine stories at the two ends of the building and five stories in the center. Building 15 includes three concrete slabs that increase the total mass while not contributing to the lateral stiffness of the building. Similarly, building 17 features concrete slabs in the top seven stories, which results in higher mass on top and thus lower fundamental natural frequency. Conversely, building 25 features a massive concrete core which increases the stiffness. Furthermore, the two smaller abutting towers are increasing the stiffness in lower stories while not contributing to the larger mass in the top stories. This results in a higher fundamental natural frequency.

Different structural system types of buildings are visualized in Figure 3b. It can be observed that none of the categories in general stood out. Interestingly, even though the heavier structural materials (i.e., concrete slabs, concrete core, and masonry façade) contributed to individual buildings standing out, hybrid buildings, in general, were well aligned with the proposed equation.

Based on the high coefficient of determination, the empirical equation fits well with the analyzed buildings of height between 16 m and 85 m. It should be noted, however, that buildings that do not fall in the scope of the analyzed structural systems by having some specific features could easily deviate from the equation by more than 20 %. Those may include irregular shapes or disproportionally high mass or stiffness.

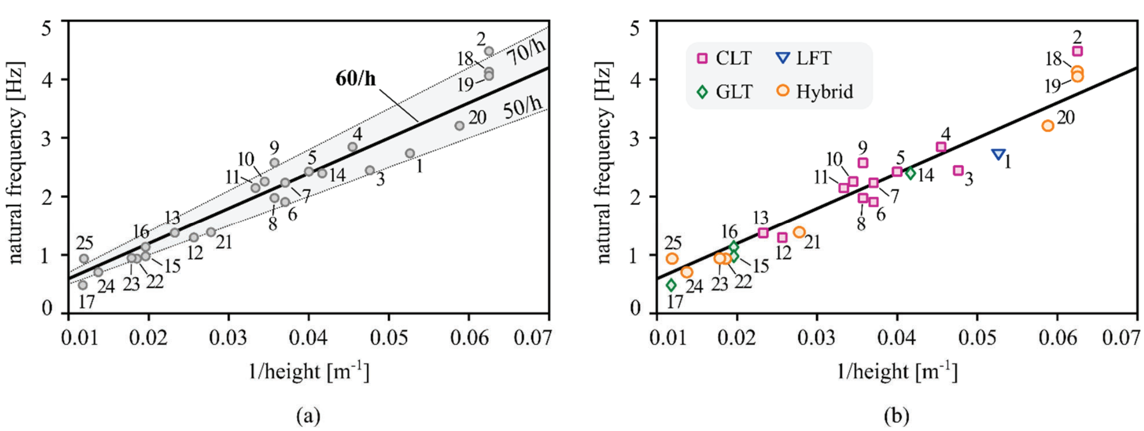

Figure 3: The fitting of the empirical equation based on data from 25 analyzed buildings, including (a) the comparison to the two alternative equations and (b) the categorization of the buildings based on their structural system.

6 – CONCLUSION

In this study, the natural frequencies of 25 multi-story timber and hybrid timber buildings, ranging from 16 m to 85 m in height, were reviewed. The empirical equations provided by various building codes, including the Eurocode, American, Canadian, Japanese, and Italian building codes, were evaluated against the collected data. The results indicate that the Japanese standards offer the most accurate predictions for timber buildings within the dataset.

Furthermore, a new empirical equation has been proposed based on the analyzed set of timber buildings. The fundamental natural frequency of timber and hybrid timber building in Hertz can be estimated to $60/h$, where h is the height of the building in meters. The architectural height of the building has been selected in this study. However, it coincided with the height of the top roof slab for most of the analyzed buildings. It should be noted that the natural frequency of the building with irregular shape or disproportionate mass or stiffness may deviate from the estimated frequency by more than 20 %.

The findings of the study highlight the need for specific considerations in building codes for timber structures to ensure reliable serviceability checks and effective design against wind-induced vibrations. Future research should focus on refining these empirical equations. With a larger number of analyzed buildings, additional parameters, such as the type of timber construction, slenderness factor, and timber-concrete ratio of structural members, could be explored.

7 – REFERENCES

[1] Kurent B, Friedman N, Brank B. Modelling of Multi-Storey Cross-Laminated Timber Buildings for Vibration Serviceability. Buildings 2024; 14:689. https://doi.org/10.3390/buildings14030689.

[2] International Organization for Standardization. ISO 10137:2007 Bases for design of structures – Serviceability of buildings and walkways against vibration. 2008.

[3] International Organization for Standardization. ISO 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 1 Hz). 1984.

[4] Reynolds T, Feldmann A, Ramage M, Chang W, Harris R. Design parameters for lateral vibration of multi-storey timber buildings. International Network on Timber Engineering Research Proceedings (INTER 2016), 2016.

[5] Council on Tall Buildings and Urban Habitat. The State of Tall Timber: A Global Audit 2025. https://www.ctbuh.org/mass-timber-data (accessed March 7, 2025).

[6] Amaddeo C, Dorn M, Martinelli L. Initial monitoring of a six-story lightweight timber frame building under different environmental conditions. Journal of Civil Structural Health Monitoring 2024. https://doi.org/10.1007/s13349-024-00867-w.

[7] Kurent B, Ao WK, Pavic A, Pérez F, Brank B. Modal testing and finite element model updating of full-scale hybrid timber-concrete building. Engineering Structures 2023;289. https://doi.org/10.1016/j.engstruct.2023.116250.

[8] Reynolds T, Bolmsvik Å, Vessby J, Chang W-S, Harris R, Jonathan B, et al. Ambient vibration testing and modal analysis of multi-storey cross-laminated timber buildings. World Conference on Timber Engineering, Oslo, 2014.

[9] Kurent B, Brank B, Ao WK. Model updating of seven-storey cross-laminated timber building designed on frequency-response-functions-based modal testing. Structure and Infrastructure Engineering 2021; 0:1–19. https://doi.org/10.1080/15732479.2021.1931893

[10] Kurent B, Friedman N, Aloisio A, Pasca D, Tomasi R, Brank B. Bayesian model updating of eight-storey CLT building using modal data. Probabilistic Engineering Mechanics 2024; 77:103642. 10.1016/j.probengmech.2024.103642.

[11] Tulebekova S, Malo KA, Rønnquist A. Dynamic identification and model calibration of connection stiffness in multi-storey cross-laminated timber buildings. Journal of Building Engineering 2023; 72. https://doi.org/10.1016/j.jobe.2023.106607.

[12] Larsson C, Abdeljaber O, Dorn M. Dynamic evaluation of a nine-storey timber-concrete hybrid building during construction. Engineering Structures 2023; 289:116344. https://doi.org/10.1016/j.engstruct.2023.116344.

 https://doi.org/10.52202/080513-0309

[13] Pettersson J, Edström T. An Evaluation of the Dynamic Behavior from Ambient Vibrations in a Timber High-Rise Building A Comparison Between Experimental In-Situ Tests and Numerical Optimization. KTH, 2024.

[14] Linderholt A, Landel P, Johansson M. Forced Response Measurements on a Seven-Story Timber Building. Conference Proceedings of the Society for Experimental Mechanics Series 2024:1–4. https://doi.org/10.1007/978-3-031-36663-5_1.

[15] Olsen MF, Hansen O. Measuring Vibrations and assessing Dynamic Properties of tall Timber Buildings. NTNU, 2016.

[16] Tulebekova S, Malo KA, Rønnquist A, Nåvik P. Modeling stiffness of connections and non-structural elements for dynamic response of taller glulam timber frame buildings. Engineering Structures 2022; 261:114209. https://doi.org/10.1016/j.engstruct.2022.114209.

[17] Reynolds T, Casagrande D, Tomasi R. Comparison of multi-storey cross-laminated timber and timber frame buildings by in situ modal analysis. Construction and Building Materials 2016; 102:1009–17. https://doi.org/10.1016/j.conbuildmat.2015.09.056.

[18] Larsson C, Abdeljaber O, Bolmsvik Å, Dorn M. Long-term analysis of the environmental effects on the global dynamic properties of a hybrid timber-concrete building. Engineering Structures 2022; 268:114726. https://doi.org/10.1016/j.engstruct.2022.114726.

[19] Manthey M, Flamand O, Jalil A, Pavic A, Ao WK. 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, Santiago: 2021.

[20] Leishman T, Ventura C, Motamedi M, Cassidy JF, Dosso SE. Ambient Vibration Testing of Canada's Tallest Wood Frame Building. Lecture Notes in Civil Engineering, vol. 514 LNCE, Springer Science and Business Media Deutschland GmbH; 2024, p. 704–11. https://doi.org/10.1007/978-3-031-61421-7_68.

[21] Flamand O, Giovannelli G, Manthey M. Data Processing to Assess Structural Damping of Tall Timber Buildings. EVACES, Milan: 2023.

[22] Malaspina M, Powell D, Verhaegh R, Dennis J, Tomek P. Dynamic performance of hybrid timber-concrete high-rise under wind induced excitation measured through on-site testing. SECED 2023 Conference, Cambridge: 2023.

[23] CEN. EN 1991-1-4:2005. Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions. Brussels, Belgique: 2005.

[24] ASCE/SEI 7-2016, American Society of Civil Engineers, 2016. Minimum design loads and associated criteria for buildings and other structures. 2016.

[25] Canadian Commission on Building and Fire Codes. National Building Code of Canada 2015 Volume 1. 2018.

[26] AIJ RLB. Recommendation for loads on buildings, Architectural Institute of Japan. 2004.

[27] Ministero delle Infrastrutture e dei Trasporti. Norme tecniche per le costruzioni (NTC). 2008.