Vibration-Based Structural Health Monitoring of Timber Structures

Vibration-Based Structural Health Monitoring of Timber Structures

Angelo Aloisio[1,5(✉)], Dag Pasquale Pasca[2], Pier Francesco Giordano[3], Marco Civera[4], Marco Martino Rosso[4], Maria Pina Limongelli[3], Thomas P. S. Reynolds[8], Chiara Bedon[6], and Blaž Kurent[7]

[1] Department of Civil, Construction-Architectural and Environmental Engineering, Università degli Studi dell'Aquila, L'Aquila, Italy

[2] Norsk Treteknisk Institute (Norwegian Institute of Wood Technology), Oslo, Norway

[3] Department of Architecture, Built Environment and Construction Engineering, Politecnico di Milano, Milan, Italy

[4] Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Turin, Italy

[5] Faculty of Science and Technology, Norwegian University of Life Sciences, Ås, Norway

angelo.aloisio@univaq.it

[6] Department of Engineering and Architecture, Università degli Studi di Trieste, Trieste, Italy

[7] Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana, Slovenia

[8] School of Engineering, University of Edinburgh, Edinburgh, UK

1 Introduction

Buildings and other civil structures can be "interrogated" through their vibration signatures: because natural frequencies, mode shapes and damping depend on mass, stiffness and energy-dissipation mechanisms, measuring ambient or forced responses reveals those properties without destructive tests. Two complementary approaches are in routine use: ambient/operational modal analysis, which exploits traffic, wind, human activity or micro-tremors as unmeasured inputs, and experimental modal analysis, which relies on shakers or vibrodynes to provide known forces [1–3]. Data are gathered with temporary or permanent networks of accelerometers and loggers; short campaigns suffice for finite element model calibration, whereas long-term installations capture the influence of temperature, humidity or occupancy on modal behaviour. The same information underpins vibration-based damage detection and post-event safety checks. Yet research on timber, especially multi-storey and hybrid systems, lags behind other materials, even though wood's moisture- and temperature-sensitive properties, and its susceptibility to biological degradation, make continuous structural health monitoring (SHM) highly desirable for verifying the flexibility and strength assumed at design.

G. Fink et al. (Eds.): *Holistic Design of Taller Timber Buildings*, SPRTRCIENG, pp. 94–103, 2025.
https://doi.org/10.1007/978-3-032-02098-7_8

2 Applications of Vibration-Based Monitoring to Timber Structures

Due to the relatively immature state of the research in this specific sector, there is a lack of standardised guidelines and best practices for implementing vibration-based SHM systems in timber structures. This strongly hampers practitioners to adopt these technologies consistently. Apart from these general considerations, each timber-based solution presents its own specific challenges and requires dedicated precautions and arrangements.

For CLT structures, since the most critical failure mode (rolling shear failure [4]) involves delamination, adhesive failure, and/or cohesive failure between two adjacent CLT layers [5], researchers have investigated the integration of different kinds of SHM sensors (measuring both the static or dynamic behaviour of the structure and the environmental conditions) directly within the layers of CLT panels. However, embedding sensors within timber members, even relatively small ones such as strain gauges or fiber optic sensors, can be labor-intensive and may require specialized techniques to ensure proper installation and long-term durability. Furthermore, embedding sensors within glued layers can be challenging, as the adhesive layer may interfere with the sensor's performance – for instance, leading to stress concentrations that can cause premature failure of the sensor [6]. Degradation of the adhesive or the wood-adhesive interface (due to ageing and/or environmental conditions, such as moisture, temperature variations, and ultraviolet radiation) can lead to false alarms or missed detection [6]. Nevertheless, embedded sensors have been proven time and time again to be very effective, especially for moisture content monitoring at various depths and locations [7,8]. In this specific regard, several researchers (e.g. [9] and [10]) emphasize the importance of carefully positioning moisture sensors both at critical locations (like joints, edges, and other areas prone to moisture exposure) and at different depths inside the material. Monitoring moisture at different depths provides insights into the moisture distribution through the CLT cross-section; in fact, timber members' response to changes in the surrounding climate is slower for larger members and, consequently, moisture gradients can develop and cause moisture-induced stresses [11]. The same considerations should be extended to vibration-measuring sensors, such as the classic piezoelectric or MEMS-based accelerometers, also to account for the high variability of mechanical properties in wood, to strategically place the sensors at critical locations.

Hybrid timber-based structures (including CLT hybrid structures), which combine timber with other materials such as steel or concrete, present additional challenges for SHM [12]. SHM sensors and techniques need to address the unique challenges posed by the interaction between different materials and their respective responses to loading and environmental conditions. That is achieved by monitoring the performance of the interfaces between timber and other materials to ensure the local structural integrity of the hybrid system. Due to this and the previous point, it is clear that (i) timber structures require, more than other construction with other building materials, sensors at many locations; (ii) sensors for static and dynamic monitoring should be always paired with environmental sensors, to adjust the measurements for the local environmental and operational factors (EOFs). Again, this aspect is more relevant in timber than in other materials. Therefore, the integration of multiple sensors into 'sensing nodes' is beneficial; furthermore, to solve the practical issues related to cabling, wireless sensor networks should be preferred, to allow optimal placement without technical constraints. Wireless communication protocols, such as LoRa and other low-power wide-area network technologies, are becoming more and more adopted for such SHM applications thanks to their long-range, low-power data transmission capabilities.

Hence, it is crucial to establish how far research on analysing the dynamic behaviour of timber buildings has gone to highlight critical issues and knowledge gaps. The literature on this topic is reviewed, highlighting similarities and differences to other structures and identifying future research needs and directions. First, an overview of the modal identification of timber buildings is provided. After that, the state of the research on damage identification and model calibration is investigated.

The literature on ambient vibration tests (AVTs) and forced vibration tests (FVTs) on civil structures is vast. According to the authors' knowledge, the first AVT on a timber building was performed by Ellis and Bougard in 2001 [13]. The tests were conducted on a full-size, six-storey timber framed structure constructed inside BRE's Cardington laboratory. They performed both FVTs and AVTs at different stages of construction, which made it possible to evaluate the contribution to the global stiffness of the timber frame alone, the staircase, and the finishing and cladding (bricks). The results of their research indicate that the building's non-structural components play a large role in the contribution to the lateral stiffness of the building at service levels. More recently, some other researchers have attempted to extract the modal properties of mid-rise timber buildings (Reynolds et al. [14,15], Feldmann et al. [16]) using operational modal analysis (OMA) methods. The research conducted by Reynolds and colleagues constitutes probably the largest database of AVT performed on timber structures in Europe to date. They tested different timber structural archetypes: post and beam, timber-framed, pure CLT and hybrid timber-concrete structures. It is also worth mentioning the tests performed in Germany and Austria on eight timber observation towers (with a height of up to 45 m), a 100 m tall wind turbine and three multi-storey residential timber buildings (with a height of up to 26 m). The findings of all these testing campaigns have allowed for assessing the simplified relationship between height and natural frequency for multi-storey buildings given in Eurocode 1.

In North America, where there is a deeply-rooted tradition of wooden frame housing, efforts have been made to understand the dynamic behaviour of smaller low-rise residential buildings, see Mugabo et al. [17], and all the infield investigations on light-frame wood buildings by Hafeez et al. [18–20]. Kim et al. [21] combined vibration and force measurements. They used load cells between the column and foundation stone to measure axial column force, and ambient vibration tests were performed to measure natural vibration frequency and mode shape.

The results of these campaigns shed some light on the dynamic behaviour of tall timber buildings, providing viable information concerning stiffness and damping of the tested structures to designers and stakeholders [22]. Nevertheless, extensive dynamic tests on mid-rise and high-rise timber structures represent a missing part, although some research has been conducted [23–26]. This will aid in learning important lessons and enhance the engineering community's confidence towards using this material.

Damage, such as cracks and reduction of cross sections in structural members, can modify the dynamic response of structures [27]. Thus, vibration data are processed to extract damage-sensitive features (DSFs) and ultimately obtain damage indices which alert about variations of DSFs between a reference and the current state of the structure [28]. According to the available resources (e.g., the number and location of sensors) different levels of damage identification can be attained [29], namely: (i) damage detection (alert about the existence of damage); (ii) damage localization (find the position of damage); (iii) damage quantification (assess the gravity of damage); (iv) damage prognosis (forecast the evolution of damage). The dynamic properties of a structure do not vary only due to the occurrence of damage. EOFs, such as ambient temperature, humidity, wind conditions and structural usage, can modify the properties of healthy structures. This is a major concern in damage identification.

Variations of EOFs might hide the effect of structural anomalies and hamper damage identification. Besides, variations in the dynamic behaviour due to EOFs might be erroneously attributed to damage. Therefore, the influence of EOFs on different materials and structural typologies must be carefully understood and considered for damage identification purposes.

In addition to temperature and relative air humidity, one of the main concerns in the case of timber buildings is the moisture content (MC), which influences several properties of timber, such as strength, density, and elastic modulus. Larsson et al. [30] were the first to carry out long-term monitoring of a hybrid timber building and investigated the relationship between environmental factors and the dynamic response of a hybrid timber-concrete building. The authors have tracked the modal parameters, i.e., natural frequencies, modal shapes, and damping ratios, for three years, together with hygrothermal parameters, i.e., temperature, relative humidity, absolute humidity, and moisture content. The results of the long-term monitoring show that modal frequencies change with the temperature, showing maximum and minimum values in early autumn and early spring, respectively. In contrast, damping ratios did not present seasonal variations. Furthermore, it is observed that the modal frequencies decrease in the first year after construction due to the drying out of timber elements. In [31], the results of a 3-year monitoring campaign on a Pres-Lam building are presented. In this case, the results show that temperature and relative humidity, as well as post-tensioning losses, do not affect the structure's dynamic behaviour. Recently, Aloisio et al. [32] investigated the effect of MC on the dynamic properties of an eight-storey CLT building and related the moisture content variation to the shear modulus G through model updating, based on a model developed in [26].

Nevertheless, the specific effects of varying moisture content (MC) on the dynamic properties of timber-made structures and infrastructures remain largely underinvestigated. MC monitoring, per se, is quite commonly performed, at least since the late 2000s. This is also referred to as hygrothermal monitoring (see e.g. [33]). These embedded sensing capabilities represent the natural progression from portable pin-type moisture meters, which can be used to manually measure moisture content at the surface or at different depths of the CLT elements during construction, but require human technicians and can only provide a snapshot of moisture levels at specific points in time. Especially for timber infrastructures, the technology was successfully tested on several wood bridge case studies in Switzerland [34,35] and several similar field tests in Germany, with applications to 21 large-span timber structures [36] and other bridges and structures [37,38]. In one case, the MC monitoring system reportedly remained operational for five years without the need for maintenance. Similar MC applications were tested on 17 modern and historical wooden bridge constructions in central Europe [39], in the USA during the Development of the 'Smart Timber Bridge' program [40], in Norway [41], Finland [42], and Sweden (both in road bridges and pedestrian ones)[43]. However, out of all these examples, only the last one [43] was paired with accelerometric readings. Other noteworthy and successful field applications of combined MC-dynamic monitoring are represented by the George W. Peavy Forest Science Complex (or "Peavy Hall") a large timber building monitored during its construction, where researchers assessed the building's long-term performance including monitoring moisture levels and structural vibrations in their study [44]; the House of Natural Resources (HoNR) in Zürich, Switzerland [45]; and the University of British Columbia (UBC) Tallhouse [46]. Therefore, the moisture-related EOFs on modal parameters and derived DSFs will require further experimental investigations.

It is also worth mentioning that MC and dynamic monitoring can (and should) be paired, as internal moisture is notoriously a potential leading cause for damage, for different reasons: sustained exposure to moisture content levels above 20%, due to moisture/water intrusion, localized moisture accumulation, water entered during construction or assembly and trapped inside, and/or other phenomena, can lead to damage by several species of wood-decaying fungi and mould growth; while in-service drying can cause the development of cracks [47]. In certain cases, these occurrences may happen in the inner layers of CLT roof and walls, without signs noticeable through visual inspections on the external surfaces. Therefore, without proactive MC monitoring and management, the negative effects could be either direct, due to the insurgence of moisture-related problems, or indirect, due to the damage-unrelated perturbations in the identified modal parameters.

One of the most promising techniques in the field of structural health monitoring (SHM) for timber structures is vibration-based analysis. This method involves the use of sensors to detect and analyze vibrations within a structure, which can reveal critical information about its integrity and any potential damage. Vibration-based SHM is particularly beneficial for timber structures as it provides a non-invasive means to continuously monitor their condition, thus helping to prevent catastrophic failures and prolong their lifespan.

The research by Suzuki et al. [48] explores the use of machine learning techniques to enhance the accuracy of SHM systems for timber structures. By employing piezoelectric sensors to capture vibration waveforms and neural networks to classify damage locations, the study achieved an impressive 83.8% accuracy in identifying damage even in previously unlearned timber pieces. This demonstrates the potential of advanced machine learning methods to generalize across different timber samples, making SHM systems more robust and reliable. Similarly, Chunyu et al. [49] have developed a specialized device for monitoring vibrations in ancient timber structures. This innovation addresses the practical challenges of securing sensors in delicate, historical buildings. The device's design ensures stable and accurate vibration monitoring, which is essential for detecting structural issues early and implementing timely maintenance. Zhibin et al. [50] introduced a health monitoring device designed to improve the accuracy and ease of installation for vibration monitoring in ancient wooden buildings. Their approach enhances the practicality of long-term SHM by simplifying the alignment of monitoring components, thereby ensuring consistent and reliable data collection. This method is particularly useful for historical structures where precision and minimal invasiveness are critical. Another significant contribution is from Oiwa et al. [51], who proposed an AI-based system for continuous monitoring of timber health using piezoelectric sensors. By applying machine learning techniques such as k-nearest neighbor and support vector machine, their system demonstrated strong classification performance in identifying structural damage. This integration of AI and SHM underscores the potential for highly automated, accurate, and efficient monitoring systems that can operate with minimal human intervention.

3 Conclusions

Vibration-based structural health monitoring has proved to be a powerful, non-destructive tool for characterising, calibrating and safeguarding civil structures, yet its systematic application to timber remains in its infancy. The studies reviewed in this chapter show that modal testing (operational or forced) can reveal stiffness, damping and mass changes caused by moisture cycling, duration-of-load effects and biological decay that are unique to wood, while also supporting damage localisation and finite-element model updating. Progress is nevertheless constrained by the pronounced anisotropy and spatial heterogeneity of timber, by the strong, often coupled influence of temperature and especially moisture content on identified modal parameters, and by the absence of standardised protocols for sensor placement, data correction and feature normalisation under environmental and operational factors. Recent field campaigns on mid-rise buildings and bridges confirm that multi-year datasets, coupled with embedded moisture probes and wireless accelerometer networks, are essential for disentangling true structural change from reversible hygro-thermal trends [30,32]. At the same time, machine-learning classifiers trained on high-frequency vibration signatures, sometimes augmented with local piezoelectric actuation, have reached damage-identification accuracies above 80% on unlearned specimens [48,51], signalling a viable path toward automated, low-maintenance monitoring of both modern CLT and heritage timber. To translate these advances into routine practice, future work must establish harmonised guidelines that link sensor networks with moisture and temperature measurements, quantify acceptable environmental correction ranges for modal features, and define reliability targets for algorithmic decision support. Only then can vibration-based SHM fulfil its dual promise of ensuring the safety of ever-taller timber buildings and preserving the embodied carbon advantage that makes them attractive in the first place.

Acknowledgments. The CA20139 - Holistic design of taller timber buildings (HELEN) is gratefully acknowledged for networking support.

References

1. Rainieri, C., Fabbrocino, G.: Output-only modal identification. In: Operational Modal Analysis of Civil Engineering Structures, pp. 103–210. Springer, New York (2014). https://doi.org/10.1007/978-1-4939-0767-0_4
2. Pasca, D.P., Aloisio, A., Rosso, M.M., Sotiropoulos, S.: Pyoma and pyoma_gui: a python module and software for operational modal analysis. SoftwareX **20**, 101216 (2022)
3. Pasca, D.P., Margoni, D.F., Rosso, M.M., Aloisio, A.: Pyoma2: an open-source python software for operational modal analysis. In: International Operational Modal Analysis Conference, pp. 423–434, Springer, Cham (2024)
4. Popovski, M., Chen, Z., Gafner, B.: Structural behaviour of point-supported CLT floor systems. In: 4th World Conference on Timber Engineering (WCTE2016) (2016)
5. Flores, E.S., Saavedra, K., Hinojosa, J., Chandra, Y., Das, R.: Multi-scale modelling of rolling shear failure in cross-laminated timber structures by homogenisation and cohesive zone models. Int. J. Solids Struct. **81**, 219–232 (2016)
6. Aicher, S., Reinhardt, H.-W., Garrecht, H.: Materials and joints in timber structures. Recent Dev. Technol. (2014)
7. Kellgren, L.V., Seeberg, A.C., Hagle, D., Øvregård, J., Rasmussen, J.: a moisture management strategy for CLT using sensor technology to create a robust Norwegian school. In: World Conference on Timber Engineering (WCTE 2023) (2023)
8. Strang, M., Leardini, P., Shirmohammadi, M.: Validating moisture-safe energy efficient CLT assemblies in hot and humid climates using experimental testing. In : World Conference on Timber Engineering (WCTE 2023) (2023)
9. Time, B., Andenæs, E., Karlsen, T., Geving, S., Kvande, T.: Moisture safety strategy for construction of CLT structures in a coastal nordic climate. In: Journal of Physics: Conference Series, vol. 2654, 13th Nordic Symposium on Building Physics (NSB-2023) (2023)

10. Tamagnone, G., Hairstans, R., Martin, J., Edmondson, V.: Method for monitoring the moisture response of a cross laminated timber (CLT) panel buildings. In: 2nd International Conference on Moisture in Buildings 2023 (ICMB23) (2023)
11. Ranta-Maunus, A.: Effects of Climate and Climate Variations on Strength, pp. 153–168. Wiley, Hoboken (2003)
12. Aloisio, A., et al.: Vibration analyses of an hybrid concrete and cross-laminated timber building case study. In: Italian Workshop on Shell and Spatial Structures, pp. 309–318, Springer, Cham (2023)
13. Ellis, B., Bougard, A.: Dynamic testing and stiffness evaluation of a six-storey timber framed building during construction. Eng. Struct. **23**(10), 1232–1242 (2001)
14. Reynolds, T., Harris, R., Chan, W.: Dynamic response of tall timber buildings to wind load. In: 35th Annual Symposium of IABSE/52nd Annual Symposium of IASS/6th International Conference on Space Structures, London (2011)
15. 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)
16. Feldmann, A., Huang, H., Chang, W., Harris, R., Dietsch, P., Gräfe, M., Hein, C.: Dynamic properties of tall timber structures under wind-induced vibration. In: World Conference on Timber Engineering (WCTE 2016) (2016)
17. Mugabo, I., Barbosa, A., Riggio, M.: Dynamic characterization and vibration analysis of a four-story mass timber building. Front. Built Environ. **5** (2019)
18. Hafeez, G., Doudak, G., McClure, G.: Effect of nonstructural components on the dynamic characteristics of light-frame wood buildings. Can. J. Civ. Eng. **47**(3), 257–271 (2020)
19. Hafeez, G., Doudak, G., McClure, G.: Dynamic characteristics of light-frame wood buildings. Can. J. Civ. Eng. **46**(1), 1–12 (2019)
20. Hafeez, G., Doudak, G., McClure, G.: Establishing the fundamental period of light-frame wood buildings on the basis of ambient vibration tests. Can. J. Civ. Eng. **45**(9), 752–765 (2018)
21. Kim, Y.-M., Kim, Y.-M., Kim, H.-J., Ha, T.-U., Shin, E.-M., Kim, W.-J.: Analysis of roof load and dynamic characteristics of traditional timber building considering column axial force and ambient vibration measurement. J. Architectural Inst. Korea **37**(11), 271–280 (2021)
22. Tulebekova, S., Malo, K.A., Rønnquist, A., Nåvik, P.: Modeling stiffness of connections and non-structural elements for dynamic response of taller glulam timber frame buildings. Eng. Struct. **261**, 114209 (2022)
23. Aloisio, A., Pasca, D., Tomasi, R., Fragiacomo, M.: Dynamic identification and model updating of an eight-storey clt building. Eng. Struct. **213**, 110593 (2020)
24. Kurent, B., Brank, B., Ao, W.: Model updating of seven-storey cross-laminated timber building designed on frequency-response-functions-based modal testing. Struct. Infrastruct. Eng. **19**(2), 178–196 (2023). cited By 12
25. 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)
26. Kurent, B., Friedman, N., Aloisio, A., Pasca, D., Tomasi, R., Brank, B.: Bayesian model updating of eight-storey CLT building using modal data. Probab. Eng. Mech. **77**, 103642 (2024)
27. Peeters, B., De Roeck, G.: One-year monitoring of the z24-bridge: environmental effects versus damage events. Earthq. Eng. Struct. Dyn. **30**(2), 149–171 (2001)

28. Farrar, C.R., Worden, K.: An introduction to structural health monitoring. Philos. Trans. R. Soc. A: Math. Phys. Eng. Sci. **365**(1851), 303–315 (2007)
29. Rytter, A.: Vibrational based inspection of civil engineering structures (1993)
30. Larsson, C., Abdeljaber, O., Bolmsvik, A., Dorn, M.: Long-term analysis of the environmental effects on the global dynamic properties of a hybrid timber-concrete building. Eng. Struct. **268** (2022)
31. Granello, G., Palermo, A.: Monitoring dynamic properties of a pres-LAM structure: trimble navigation office. J. Perform. Constr. Facil. **34**(1), 04019087 (2020)
32. Aloisio, A., Pasca, D.P., Kurent, B., Tomasi, R.: Long-term continuous dynamic monitoring of an eight-story CLT building. Mech. Syst. Signal Process. **224**, 112094 (2025)
33. Schmidt, E., Riggio, M.: Monitoring moisture performance of cross-laminated timber building elements during construction. Buildings, **9**(6) (2019)
34. Tannert, T., Berger, R., Müller, A.: Remote moisture monitoring of timber bridges: a case study (2011)
35. Franke, B., Franke, S., Müller, A.: Case studies: long-term monitoring of timber bridges. J. Civ. Struct. Health Monit. **5** (2015)
36. Dietsch, P., Gamper, A., Merk, M., Winter, S.: Monitoring building climate and timber moisture gradient in large-span timber structures. J. Civ. Struct. Health Monit. **5** (2015)
37. Brischke, C., Rapp, A.O., Bayerbach, R.: Measurement system for long-term recording of wood moisture content with internal conductively glued electrodes. Build. Environ. **43**(10), 1566–1574 (2008)
38. Brischke, C., Rapp, A.O., Bayerbach, R., Morsing, N., Fynholm, P., Welzbacher, C.R.: Monitoring the “material climate" of wood to predict the potential for decay: Results from in situ measurements on buildings. Build. Environ. **43**(10), 1575–1582 (2008)
39. Fojtík, R.: Moisture content analysis of wooden bridges. Wood Res. **64** (2019)
40. Phares, B.M., Pence, T.L., Wacker, J.P., Hosteng, T.K.: Development of a smart timber bridge (phase iii): moisture and strain sensor investigation for historic covered bridges (2019)
41. Mahnert, K.-C., Hundhausen, U.: A review on the protection of timber bridges. Wood Mater. Sci. Eng. **13**(3), 152–158 (2018)
42. Seppälä, M., Ilgın, H.E., Karjalainen, M., Pajunen, S.: An analysis on finnish wooden bridge practices. Appl. Sci. **13**(7) (2023)
43. Björngrim, N.: Monitoring of a Timber Footbridge. PhD dissertation (2015)
44. Baas, E.J., Riggio, M., Barbosa, A.R.: A methodological approach for structural health monitoring of mass-timber buildings under construction. Constr. Build. Mater. **268**, 121153 (2021)
45. Granello, G., Leyder, C., Frangi, A., Palermo, A., Chatzi, E.: Long-term performance assessment of an operative post-tensioned timber frame structure. J. Struct. Eng. **145**(5), 04019034 (2019)
46. Kaya, Y., Ventura, C.E., Taale, A.: An ambient vibration test of an R/C wall of an 18-story wood building at the UBC campus. In: Caicedo, J., Pakzad, S. (eds.) Dynamics of Civil Structures, Volume 2. CPSEMS, pp. 315–320. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-54777-0_39
47. Palma, P., Steiger, R.: Structural health monitoring of timber structures - review of available methods and case studies. Constr. Build. Mater. **248**, 118528 (2020)
48. Suzuki, K., Ito, T., Koike, K., Kawahara, T., Ke, M., Mori, K.: Improvement of generalization performance for timber health monitoring using machine learning (2020)

49. Chunyu, Q., Xiao, D., Jianguo, Z., Kai, Z., Wei, W., Junlian, L.: Timber structure ancient building vibration monitoring vibration pickup installation device (2016)
50. Zhibin, S., Shengnan, S., Zhaobo, M.: Healthy condition monitoring device under vibration for ancient wooden building (2019)
51. Oiwa, R., Ito, T., Kawahara, T.: Timber health monitoring using piezoelectric sensor and machine learning (2017)