Materials Science and Technology

Structural health monitoring of timber structures – review of available methods and case studies

Fonds zur Förderung der Wald- und Holzforschung
Projekt 2016.20 Bauwerks- und Bauteilüberwachung im Holzbau

Pedro Palma and René Steiger

July 2018

Structural Engineering Research Lab
Empa – Materials Science and Technology

(publication version)

Contents

Acknowledgements

The authors gratefully acknowledge the financial support from the *Bundesamt für Umwelt BAFU*, namely the *Fonds zur Förderung der Wald- und Holzforschung* (*Projekt* 2016.20 *Bauwerks- und Bauteilüberwachung im Holzbau*).

The authors also thank the companies that answered the survey on structural monitoring (listed in Section 7).

Summary

A wide variety of non-destructive testing (NDT) and damage identification techniques are nowadays available for the structural health monitoring (SHM) of structures. During the last decades, the potential benefits associated with SHM led to a substantial increase in related research. SHM is particularly suited for structures subject to long-term movement or degradation, to improve future design based on experience, for new construction systems, and to face the decline in construction and growth in maintenance needs (Brownjohn 2007).

The anisotropy, moisture dependency, and high variability of timber properties, the wide range of available sensors, the relative novelty of some sensors, and the need to calibrate them for each new configuration, makes specifying and implementing a monitoring system in a timber structure a non-trivial task, heavily dependent on previous experience. An overview of current SHM strategies for timber structures was, therefore, deemed necessary to frame the current situation, assess the scope of applicability of current approaches, and identify relevant methods that can be further developed.

A broad variety of NDT methods has been developed and applied to wood and structural timber. However, not all NDT methods can be efficiently used for monitoring purposes and even fewer can be integrated in automated SHM systems. To be used in a SHM system, a NDT method must not only be able to continuously and reliably assess a specified property or parameter, but also comply with various operational requirements. This gap between research on NDT and practical applications can explain, in part, the reduced number of reported long-term monitoring studies of timber structures. Nevertheless, as the use of timber structures for more demanding end uses increases, namely higher buildings and structures with longer spans and/or higher loads, so does the interest in monitoring them.

In last 10 years, some medium/long-term SHM studies have been conducted in timber structures. Most of them are focused on monitoring the moisture content of wood and the indoor/outdoor climate, due to its relevance to the behaviour and durability of timber and the low cost and simplicity of the necessary equipment. This has proven to be a reliable and effective strategy that is able to detect damage at an early stage, if the location of the sensors is adequately chosen.

Acoustic methods can be divided in ultrasonic and acoustic emission methods. Ultrasonic methods are widely and successfully used in non-destructive assessment of timber, namely to detect cracks and delaminations on structural members. Another advantage of ultrasonic methods is that the required equipment is also easy to use. The main disadvantages are the influence of the surface preparation and the difficulty of interpreting the results, namely in irregular and non-homogeneous elements. Acoustic emission methods are able to detect damage at a very early stage. Their main disadvantage is the practical difficulty of implementation in structural-sized elements, due to the required instrumentation and difficulty in discerning the acoustic emission signals from the background noise. So far, no techniques based on these methods have been integrated in SHM systems.

Vibration-based methods are based on identifying damaged states through changes in the dynamic response of a structure. Many NDT methods have a limited spatial reach and require that the area

where damage is likely to occur is known in advance. Vibration-based methods are one of the few that would be able to monitor global changes in the structure, even using only ambient excitations. Their main disadvantage is that the lower frequencies that are typically measured are less sensitive to damage and might not be enough to identify the damage and even less to locate it, unless a high number of sensors is used.

Optic methods allow a contact-free determination of displacements, surface deformations, and even vibrations. These methods have a large variety of uses, including measuring over very long and very short distances (e.g. displacements in bridges, surface strains and cracks on structural elements), and comprise a wide range of global and local techniques. Global methods can be used to assess damage that has an impact on the deformation of the structure, whereas local methods are limited to defects that reach the surface of the members or, at least, significantly influence surface strains. The use of optic methods in the automated monitoring of deformations and displacements is undergoing quick developments, namely through the use of photogrammetric methods based on image-analysis techniques. These methods do not require direct access to the structure, can provide large amounts of information, and can be set up with lower-cost components. However, they usually still exhibit lower accuracies than traditional surveying methods. Progress in this field is under heavy development, both regarding hardware and image-processing algorithms, and improved accuracies at lower costs should be possible.

The use of fibre-optic sensors is also a promising field, namely for monitoring strains in timber structural elements. Fibre-optic strains sensors can provide average strains over longer lengths than traditional strain sensors, which is particularly adequate for a non-homogeneous and highly variable material as timber. The advantages of using fibre-optics sensors are the possibility of adapting them to measure various parameters, the possibility of having multiple sensors in a single optic fibre, their resistance to harsher environments, and their ability to also be used for high-frequency measurements. The disadvantages are the high cost of producing the sensors and of the data acquisition instrumentation, and the general lack of experience on how to install properly install these sensors in timber elements

The main results of the survey conducted among several timber engineers on the monitoring of timber structures show that monitoring is already widely used, namely for important or special structures and that monitoring strategies are mostly decided on a case-by-case basis. It is recognised that monitoring may assist in preventing damage and that the most important parameters to be monitored are the moisture content of wood, the indoor and outdoor climate, deformations and displacements, cracks and delamination of bond lines, and pre-stressing forces. As one of the reasons hindering theimplementation of SHM in practice, designers mentioned that it is often not clear who should bear the costs of monitoring (the owner of the building, the designer, or the main contractor). It was also mentioned that proposing a monitoring system might raise questions about the quality of the design. According to the designers, the most important features that monitoring systems should include were wireless data transmission, ease of use (installation, operation, and interpretation of the results) and low cost. This is in agreement with the most recent SHM case studies (see Section 6) and supports the need to bridge the gap between well-established NDT methods and their use in SHM in practice.

Zusammenfassung

Für die Bauwerksüberwachung (Structural Health Monitoring, SHM) stehen heute eine Vielzahl von zerstörungsfreien Prüfmethoden (ZfP-Methoden) und Verfahren zur Schadenserkennung zur Verfügung. In den letzten Jahrzehnten haben die potenziellen Vorteile von SHM zu einer erheblichen Zunahme der damit verbundenen Forschung geführt. SHM eignet sich besonders für Bauwerke, welche langfristigen Deformationen oder einer Degradation unterliegen, um die Sicherheit bei der Planung von Tragwerken auf Grund der Erfahrungen aus SHM zu erhöhen, für neue Bausysteme, für die noch wenig Erfahrung vorliegt und zur Bewältigung des im Vergleich zum stagnierenden Neubau zunehmenden Bedarfs an der Erhaltung bestehender Bauwerke (Brownjohn 2007).

Die Anisotropie, Feuchteabhängigkeit und grosse Variabilität der Holzeigenschaften, die grosse Auswahl an verfügbaren Sensoren, die relative Neuheit einiger Sensoren und die Notwendigkeit, sie für jede neue Konfiguration zu kalibrieren, machen die Spezifikation und Implementierung eines Überwachungssystems in einem Holztragwerk zu einer nicht trivialen Aufgabe, welche stark von früheren Erfahrungen abhängt. Die Zusammenstellung des vorliegenden Überblicks über die aktuellen SHM-Strategien für Holzbauwerke wurde daher als notwendig erachtet, um die aktuelle Situation zu erfassen, den Anwendungsbereich aktueller Ansätze zu bewerten und für den Holzbau relevante Methoden zu identifizieren, welche bereits existieren oder weiterentwickelt werden können.

Eine breite Palette von ZfP-Methoden wurde entwickelt und auf Baustoffe und Bauteile aus Holz angewandt. Allerdings lassen sich nicht alle ZfP-Methoden effizient zur Überwachung einsetzen und viele können nicht in automatisierte SHM-Systeme integriert werden. Um in einem SHM-System eingesetzt werden zu können, muss ein ZfP-Verfahren nicht nur in der Lage sein, eine bestimmte Eigenschaft oder einen Parameter kontinuierlich und zuverlässig zu messen und zu bewerten, sondern auch verschiedene betriebliche Anforderungen zu erfüllen. Diese Lücke zwischen der Forschung zur ZfP und praktischen Anwendungen kann zum Teil die geringere Zahl der verfügbaren Langzeit-Monitoring-Studien an Holzkonstruktionen erklären. Mit zunehmendem Einsatz von Holztragwerken für anspruchsvolle Endnutzungen (höhere Gebäude und Tragwerke mit grossen Spannweiten und/oder hohen Lasten) steigt auch das Interesse an deren Überwachung.

In den letzten 10 Jahren wurden einige umfangreiche SHM-Studien durchgeführt. Die meisten von ihnen konzentrierten sich auf die Überwachung des Feuchtegehalts von Holz und des Innen- und Aussenklimas, da diese Parameter für das Verhalten und die Dauerhaftigkeit von Holztragwerken von grosser Bedeutung sind, die Kosten der notwendigen technischen Ausrüstung gering und die Bedienung der Geräte einfach sind. Wenn der Standort bzw. die Lage der Sensoren angemessen gewählt wird, hat sich dies als zuverlässige und effektive Strategie erwiesen, um Schäden frühzeitig erkennen zu können.

Die im Rahmen der ZfP eingesetzten akustischen Verfahren lassen sich in Ultraschall- und Schallemissionsverfahren unterteilen. Ultraschallverfahren werden in der zerstörungsfreien Beurteilung von Holz häufig und erfolgreich eingesetzt, nämlich zur Erkennung von Rissen und Delaminierungen von Klebfugen an Bauteilen. Die Vorteile der Ultraschallverfahren liegen in der einfachen Handhabung

der Geräte. Die Hauptnachteile sind der Einfluss der Beschaffenheit der Oberflächen, an welche die Sensoren gekoppelt werden und die Schwierigkeit der Interpretation der Ergebnisse, insbesondere bei unregelmässigen und inhomogenen Bauteilen. Schallemissionsverfahren sind in der Lage, Schäden sehr früh zu erkennen. Ihr Hauptnachteil liegt in den Problemen bei der Anwendung in Bauteilen mit praxisgerechten Abmessungen, dies aufgrund der erforderlichen Instrumentierung und der Schwierigkeit, die Schallemissionssignale von den Hintergrundgeräuschen zu unterscheiden. Bisher wurden keine Techniken, welche auf akustischen Methoden basieren, in SHM-Systeme integriert.

Schwingungsbasierte Methoden basieren auf der Identifizierung von Schädigungen in Bauteilen und Tragwerken aus gemessenen Veränderungen im dynamischen Verhalten eines Bauteils oder Tragwerks. Viele schwingungsbasierte ZfP-Methoden sind von begrenzter räumlicher Reichweite und erfordern, dass der Bereich, in dem Schäden auftreten können, im Voraus bekannt ist. Jedoch gehören die schwingungsbasierten Methoden zu den wenigen, welche in der Lage sind, globale Veränderungen in Tragwerken zu überwachen, selbst wenn nur Umgebungsanregungen (sogenannte Ambient Excitations) verwendet werden. Der Hauptnachteil der schwingungsbasierten Methoden ist, dass die niedrigen Frequenzen, die typischerweise gemessen werden, weniger empfindlich auf Schäden reagieren und möglicherweise nicht ausreichen, um die Schäden zu lokalisieren, wenn nicht eine grosse Anzahl an Sensoren eingesetzt wird.

Optische Verfahren ermöglichen eine berührungsfreie Bestimmung von Verschiebungen, Oberflächenverformungen und sogar Schwingungen. Optische Verfahren sind vielfältig einsetzbar, auch über sehr lange und sehr kurze Distanzen (z.B. Verschiebungen in Brücken-Tragwerken und Oberflächendehnungen sowie Risse bei Bauteilen) und umfassen ein breites Spektrum an globalen und lokalen Techniken. Globale optische Verfahren können eingesetzt werden, um Schäden zu beurteilen, die sich auf die Verformung des Tragwerks auswirken, während sich lokale Verfahren auf Defekte beschränken, welche die Oberfläche der Bauteile erreichen oder zumindest die Oberflächendehnungen signifikant beeinflussen. Der Einsatz optischer Verfahren zur automatisierten Überwachung von Verformungen und Verschiebungen entwickelt sich rasant, und zwar durch den Einsatz photogrammetrischer Methoden auf Basis von Bildanalyseverfahren. Diese Methoden erfordern keinen direkten Kontakt mit dem Bauteil bzw. dem Tragwerk, können grosse Mengen an Informationen liefern und mit kostengünstigen Komponenten implementiert werden. Allerdings weisen sie in der Regel noch geringere Genauigkeiten auf als herkömmliche Vermessungsmethoden. Die Fortschritte in der Entwicklung sind gross, sowohl bei der Hardware als auch bei den Bildverarbeitungsalgorithmen und eine verbesserte Genauigkeit bei geringeren Kosten sollte zukünftig möglich sein.

Auch der Einsatz von faseroptischen Sensoren ist ein vielversprechendes Gebiet, z.B. für die Überwachung von Dehnungen in Holzbauteilen. Faseroptische Dehnungssensoren können mittlere Dehnungen über grössere Längen messen als herkömmliche Dehnungssensoren, was besonders für einen inhomogenen Baustoff mit grossen Streuungen der Eigenschaften wie Holz geeignet ist. Der Einsatz von faseroptischen Sensoren bietet mehrere Vorteile: die Möglichkeit der gleichzeitigen Messung verschiedenster Parameter; die Möglichkeit, mehrere Sensoren in eine einzige optische Faser zu integrieren; die hohe Widerstandsfähigkeit der Sensoren bei Exposition in rauen Umgebungen und die Möglichkeit, auch für Messungen mit hoher Frequenz eingesetzt zu werden. Nachteilig sind die hohen Kosten für die Herstellung der Sensoren und der Datenerfassungsgeräte und der bisher noch beschränkte Erfahrungsstand bei der Installation solcher Sensoren in Holzbauteilen.

Die Erhebung, welche bei Holzbau-Planungsbüros betreffend Überwachung von Holzbauteilen und –tragwerken durchgeführt wurde, zeigte, dass die Bauwerksüberwachung bereits weit verbreitet angewendet wird, insbesondere bei bedeutsamen oder für speziellen Konstruktionen, und dass über die einzusetzende Überwachungsstrategie bzw. -technik meist von Fall zu Fall (Bauwerks-spezifisch) entschieden wird. Aus Sicht der Planer sind die wichtigsten zu überwachenden Parameter bei Holztragwerken: der Feuchtegehalt des Holzes, das Raum- und Aussenklima, Verformungen und Verschiebungen, Risse und Delaminationen sowie Vorspannkräfte. Als Hinderungsgrund für die Implementierung eines SHM nannten die Planer das Problem, dass oft nicht klar ist, wer die Kosten der Überwachung tragen soll (der Eigentümer des Gebäudes, der Planer oder der Generalunternehmer). Es wurde auch erwähnt, dass der Vorschlag eines Überwachungssystems beim Bauherrn Fragen betreffend Qualität der Planung aufwerfen könnte. Als die wichtigsten Merkmale, welche Überwachungssysteme aus Sicht der Planer aufweisen sollten, wurden genannt: eine drahtlose Datenübertragung, eine einfache Handhabung (Installation, Bedienung und Interpretation der Ergebnisse) und geringe Kosten. Diese Antwort der Planer steht im Einklang mit den neuesten SHM-Fallstudien (s. Kapitel 6) und unterstreicht die Notwendigkeit, die Lücke zwischen dem fortgeschrittenen Stand in der Forschung zur ZfP und einer Anwendung entsprechender Methoden im Rahmen von SHM in der Praxis zu schliessen.

1. Introduction

1.1 Background

A wide variety of non-destructive testing (NDT) and damage identification techniques are nowadays available for the structural health monitoring (SHM) of civil structures. During the last decades, the potential life-safety and economic benefits associated with SHM led to a substantial increase in related research. SHM is particularly suited for structures subject to long-term movement or degradation, to improve future design based on experience, for new construction systems, and to face the decline in construction and growth in maintenance needs (Brownjohn 2007).

Regarding timber structures and elements, the most recent studies comprise the monitoring of moisture content and indoor climate, vibrations, strains, displacements, and forces (Kurz and Boller 2015). The most comprehensive medium/long-term monitoring systems have been installed quite recently and comprise *conventional* sensors (e.g. accelerometers, strain sensors, electrical displacement transducers), *NDT-based* sensors (mainly moisture content meters), and *fibre-optic* sensors (e.g. strain sensors). Due to their layered nature, modern timber members (e.g. glued laminated timber, cross laminated timber) are particularly suited to the integration of sensors during production.

The anisotropy, moisture dependency, and high variability of timber properties, the wide range of available sensors, the relative novelty of some sensors, and the need to calibrate them for each new configuration, makes specifying and implementing a monitoring system a non-trivial task, heavily dependent on previous experience. An overview of current SHM strategies for timber structures was, therefore, deemed necessary to frame the current situation, assessing the scope of applicability of current approaches and identifying relevant methods that can be further developed.

1.2 Scope and objectives

This report gives an overview of available SHM strategies for timber structures, members, and connections, and summarises the used methods and technologies. Relevant timber properties and parameters and the applicable monitoring strategies are presented and discussed. These monitoring strategies are assessed regarding *operational aspects* (what is monitored and how the monitoring is carried out), and *data acquisition aspects* (excitation methods, sensor type, number and locations, and the data acquisition, transmission, and storage equipment).

Structural monitoring strategies usually include periodic inspections, which can also employ specific NDT techniques (e.g. visual inspection, sounding, probing, resistance drilling). However, SHM is commonly associated with more automated strategies, with much shorter observation intervals, even if only during a short period (e.g. less than 1 week). This study focuses on the latter automated monitoring strategies and, therefore, techniques specific to visual inspections are not discussed. This study will also not focus on advanced data processing aspects of SHM (e.g. feature extraction, information condensation, optimisation of data transfer).

1.3 Overview

The report starts with an introduction to SHM (Section 2), followed by a discussion on specific aspects of timber structures (Section 3), principles and instrumentation of relevant NDT-based methods for SHM (Section 4), relevant parameters and corresponding monitoring techniques (Section 5), case studies (Section 6), results of the survey on SHM (Section 7), and conclusions (Section 8).

2. Structural health monitoring (SHM)

2.1 Introduction and definitions

The Swiss standard SIA 260:2013, which sets the basic principles for the design of structures, includes *monitoring* within the *preservation*-related activities and measures, which are "undertaken to ensure the continued existence of construction works" (Figure 2). This standard defines *monitoring* as the "determination and assessment of the *condition* [of constructions works] with recommendations on steps to be taken". In other words, SHM is the process of implementing a *damage* identification strategy (Farrar and Worden 2007; Worden et al. 2007), with *damage* being usually associated with a *change* in material properties, geometry, support conditions, or loading that influences the structure's current or future performance or durability. *Monitoring* is, therefore, related to the *condition evaluation* of construction works, i.e. the "evaluation of the information on the current condition of the construction and the previous development of the condition, combined with a prediction of the further development of the condition and its consequences during the remaining *service life*" (SIA 260:2013). This requires the definition of *damage scenarios*, the measurement of *damage-related properties*, the analysis of these measurements to assess the *structural health* (Farrar et al. 2001), and a prediction of the remaining service life.

The above definition of *monitoring*, by including not only the assessment of the current condition (and its previous evolution) but also its consequences on the remaining service life, cannot usually be fulfilled by a single condition/damage assessment method. Therefore, to be effective, SHM should rely on different methods. SHM also usually comprises various technologies, from sensing to data acquisition, transmission, and processing (Sohn et al. 2004).

The *condition* of the construction works can be related to various service requirements, namely regarding structural safety, serviceability, and durability. The *damage scenarios* are, therefore, usually associated with collapse or other forms of structural failure (*ultimate limit states*), or with conditions beyond which specified service requirements are no longer met (*serviceability limit states*) (EN 1990:2002). The *condition* or *damage state* assessment of the structure can be analysed from a multi-level perspective (Table 1) (Rytter 1993; Sohn et al. 2004; Balageas et al. 2006). Some experimental assessment methods might be able to address the first two levels (*existence* and *location* of damage), but models or data from damaged similar systems are required to address the third and fourth levels (*type* and *extent* of damage). The fifth level (*consequence* of damage) may require statistical analyses that include expected loads and material degradation, combining a global structural model with local damage models (Sohn et al. 2004; Balageas et al. 2006). For common structures under typical use conditions, the assessment methods described above can be relatively straightforward to implement, because there is usually a great deal of experience regarding what and where to measure and the consequences various degrees of damage (e.g. unprotected timber elements exposed to high moisture contents will experience irreversible decay). In these cases, the above-mentioned fifth level could be based on engineering judgement.

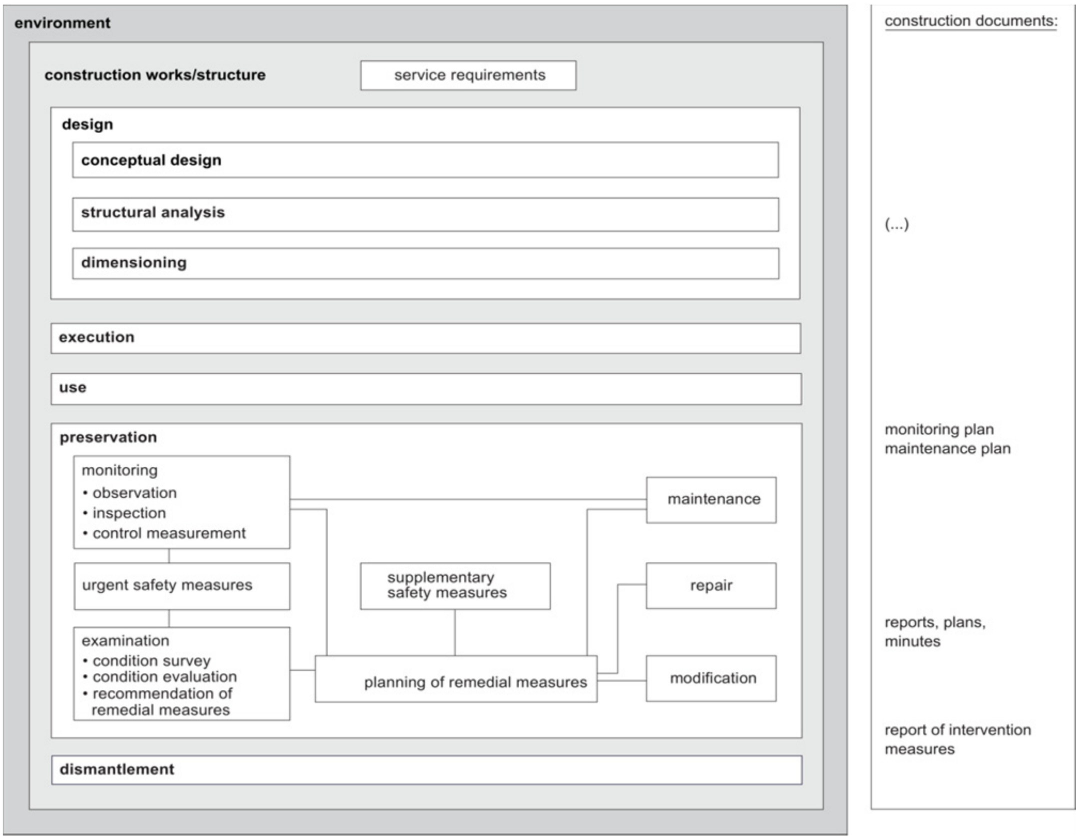


Figure 1. Relationships between different design elements (adapted from SIA 260:2013).

Table 1: Levels of assessment of structural condition or damage state (based on Rytter (1993), Sohn et al. (2004) and Balageas et al. (2006)).

Level 1	– Existence	– The assessment method gives a qualitative indication that damage might be present in the structure.
Level 2	– Location	– The assessment method gives information about the probable location of the damage.
Level 3	– Type	– The assessment method gives information about the kind of damage.
Level 4	– Extent	– The assessment method gives information about how extensive and severe the damage is.
Level 5	– Consequence	– The assessment method gives information about the actual safety of the structure given a certain damage state, i.e. a prediction of the remaining service life.

The fundamental components of a SHM system are the *data-acquisition equipment* and the *data-processing techniques*. The *data-acquisition equipment* includes *sensors* and the hardware necessary to acquire, transmit, and store the measured data. *Sensors* convert physical parameters to electric signals, which are then processed by the data acquisition system. Many physical and mechanical properties of interest are not directly measurable and, therefore, proxy measurable parameters are used instead (e.g. measuring the electrical resistance and temperature of wood to assess its moisture content). Sensors have become increasingly small and can many times be integrated during the production of the structural elements. Modern structural timber products (e.g. glued laminated timber and cross laminated timber) are particularly suited to the integration of *embedded sensors* during production, which can then be connected to a data acquisition system and log the evolution of the selected parameters. The number and location of sensors and the measurement frequency are also a fundamental aspect of any SHM system. The data-acquisition equipment might also include *actuators* to apply a predefined excitation to the structure (e.g. vibration, ultrasonic signal) so that the sensors can capture the response. The *data-processing techniques* are the algorithms used to extract relevant *features* from the measured data. In some cases this can be relatively straightforward (e.g. locally measuring the electrical resistance to estimate the moisture content), but other situations may require advanced numerical techniques (e.g. assessing of dynamic properties using vibration-based methods to estimate elastic properties).

Many SHM applications are based on adapted NDT methods, i.e. methods that are able to identify physical and mechanical properties of a material without altering its end-use capabilities (Ross and Pellerin 1994). A wide variety of NDT methods are available to assess physical and mechanical properties of structural members, some developed to be applied under controlled conditions and others to be used in situ (Kasal and Tannert 2010; Ross 2015). Implementing a NDT method in a SHM system requires its complete automation and its adaptation to different operational conditions, which might not always be possible (Kurz and Boller 2015).

The autonomy of SHM systems depends on several aspects, namely the measurement frequency and the power requirements of the sensors, actuators, and data acquisition system. High-frequency measurements SHM systems (e.g. vibration-based SHM) need to either be directly connected to the electrical grid, or run only for a short period. Systems designed to collect sparse measurements or to run only for short periods can many times run on batteries, which can make their implementation easier. Truly autonomous sensors that harvest the energy they need to operate (make measurements and transmit data) from ambient sources are still in the developmental stages, particularly when applied to SHM (Park et al 2008).

In practice SHM implementations can have various degrees of complexity, ranging from simple *passive* monitoring of a single parameter (e.g. moisture content, temperature) to sophisticated *active* monitoring systems, in which the structure is equipped with both sensors and actuators (e.g. ultrasonic wave propagation between a transmitter and a receiver). *Passive* monitoring systems are used to observe the evolution of selected parameters under *normal* environmental and operational conditions, which in some contexts is called *ambient excitation* (i.e. without a deliberate action being imposed on the structure). If, in addition to the sensors, also actuators were installed in the structure, these can generate *perturbations* (e.g. vibrations, or ultrasonic waves) which are then measured by the sensors. Depending on whether the structure is *damaged* or *undamaged*, the generated perturbations will excite the sensors differently (e.g. a crack in a structural element might change its modal frequencies, or how ultrasonic waves propagate through it).

In addition to the previous definitions, it also useful to clarify what SHM is not. SHM does not replace quality control during production, which requires that product standards are followed. SHM does not replace a maintenance plan. The maintenance plan might rely on the results of the SHM systems, but tasks (e.g. checking moisture content at predefined locations, tachymetric survey of displacements), schedules (e.g. yearly, or every *n* years), and the corresponding responsible individuals or entities must be defined regardless of the implemented SHM systems. SHM systems might include automatic alerts, which are triggered when predefined conditions are met, but an adequate information flow chain must be in place to assure that the necessary steps are then taken. In addition, checking the monitoring and alert systems must also be part of the maintenance plan. Finally, SHM does not compensate for poor design, even though it might detect its consequences (e.g. ponding effect on flat roofs due to excessive vertical deformation of the structure). In fact, some answers to the survey on SHM (Section 7) pointed out that instead of relying on monitoring, the goal should be to create less vulnerable and durable constructions that do not require monitoring.

Two other concepts that regularly appear in the context of structural monitoring are *maintenance* and *inspection*. The corresponding definitions in (SIA 260:2013) have been adopted in this document: *maintenance* are "simple and regular measures" undertaken to preserve the serviceability of the construction works, i.e. its functionality and appearance; *inspection* is the determination of "the condition by specific, and as a rule, visual and simple investigations and condition assessment" (inspections can, therefore, be part of a maintenance plan).

2.2 Advantages of SHM

Monitoring can be a way to reach specific levels of reliability, to ensure durability, and to mitigate hazards, if done in accordance with an adequate *monitoring plan*, i.e. "instructions for the monitoring specific to the construction works" (SIA 260:2013). The information provided by SHM systems can, therefore, minimise service disruptions, optimise maintenance or repair operations, and reduce maintenance costs (Mufti et al. 2001). It can also provide information that can be used to improve the design of future structures.

2.3 Guidelines for SHM

Existing guidelines on SHM of civil engineering structures focus mostly bridges and offshore structures (Daum 2013), for which repairs that require down time are to be avoided.

The *Condition Monitoring of Load-bearing Structures*. (NORSOK Standard N-005, Rev. 1), published in 1997 by the Norwegian Technology Standards Institution, provides general principles of how condition monitoring of offshore load-bearing structures should be planned, implemented and documented. It is mostly focused on periodic visual inspections and provides guidance regarding inspection methods of specific offshore structures and structural components.

The German document DGZfP-B 9 *Merkblatt über die automatisierte Dauerüberwachung im Ingenieurbau* (information sheet on automated permanent monitoring in civil engineering), published in 2000 and withdrawn in 2009, gives an overview and information on the field of application, execution, and evaluation of measurements for long-term monitoring of structures. It addresses only methods that were well-established at the time of publication and was intended to be used as a reference in the preparation of quotations and tenders as well as to carry out monitoring works.

The *Guidelines for Structural Health Monitoring – Design Manual No. 2* (Mufti et al. 2001), published by ISIS Canada (currently known as SIMTReC), focuses on techniques related to static and dynamic field testing of bridges, and periodic monitoring, but does not deal with continuous monitoring or remote data acquisition. Guidelines for selecting and protecting sensors commonly used in civil engineering applications, guidelines regarding data acquisition, and application examples are also presented.

The report on *Development of a model health monitoring guide for major bridges* (Aktan et al. 2003), published by the Intelligent Infrastructure and Transportation Safety Institute of Drexel University, UK, describes of health monitoring tools, strategies and application scenarios, focusing on experimental tools for controlled testing, short-duration monitoring, and long-duration health monitoring. A general procedure for design, calibration, and implementation of field measurement systems for SHM of bridges is presented. The report also provides guidance on selecting sensors and presents the fundamentals of data acquisition.

The *Guideline for Structural Health Monitoring* (Rücker et al. 2006) is an outcome of a European-Union-funded project. This document focuses on the assessment of loads acting on the structure, to derive realistic load models to be used in the analysis of fatigue strength and service life of structural components. It also gives an introduction to existing methods for structural condition analysis and monitoring, as well as recommendations for their application. These guidelines also cover structural damage analysis, namely procedures for damage identification and assessment. The presented application examples focus mostly bridges.

2.4 Sensors used in SHM

A thorough review of *sensors* used in SHM would be too extensive and outside of the scope of this document, but given that there are many references to these devices throughout the text, some related bibliography is presented.

- A comprehensive review of sensors for scientific, industrial, and consumer applications is presented in the *Handbook of Modern Sensors*, by Fraden (2010).
- Within the field of SHM, Mufti et al. (2001) present detailed descriptions of the most common sensors, namely to measure strains, displacements, accelerations, and temperature. Aktan et al. (2003) also present a comprehensive and detailed list of sensors commonly used in bridge monitoring, as well as performance characteristics and selection criteria, including environmental and economic considerations. Rücker et al. (2006) classify sensors according to mounting complexity and practical experience.
- Huston (2010) and Xu and He (2017) present the most up-to-date and extensive characterisations of sensors used in SHM applications. Huston (2010) lists the most common properties and parameters that are directly measurable with sensors, describes the performance characteristic to consider when selecting sensors, describes in detail an extensive list of sensors, describes data processing techniques, and addresses the design of SHM systems. The focus of Xu and He (2017) is more on vibration-based methods and structural control applications.

Given that SHM extends to a very broad array of disciplines, each using its own established terminology. For consistency purposes, the following definitions are adopted in this document, even if in some specific fields they are not so common (e.g. “strain sensor” instead of “strain gauge”):

- *transducer* – device that converts one form of energy to another (Agarwal and Lang 2005); it can either be a *sensor* or an *actuator*.
- *sensor* – transducer that responds to a stimulus (quantity, property, or condition that is sensed) by producing a signal, usually electrical (Fraden 2010).
- *actuator* – device that applies a predefined excitation (e.g. vibration, ultrasonic signal) to a structure or a structural element; requires a control signal and an energy source.
- *gauge* – instrument that measures and gives a visual display of the amount or level of the measurand.

3. Specific aspects of timber structures

Wood is a highly anisotropic material, with time, moisture and temperature-dependent properties, and exhibits a high variability of physical and mechanical properties. In structural dimensions, timber exhibits high variability not only between but also within elements, mainly due to non-homogeneities, namely *defects* (e.g. knots, grain deviation), which strongly influence its performance (Thelandersson and Larsen 2003). In the following sections, the specific aspects of the behaviour of timber structures (compared to concrete and steel structures) are presented and discussed.

3.1 Anisotropy

Wood is a strongly anisotropic material, i.e. its mechanical and strength properties are directionally dependent, exhibiting different behaviours in different directions. Particular types of anisotropy can be identified at various levels, from the scale of wooden cells and tissues to structural timber elements. The anisotropy of wood is reflected on the distinctively different mechanical behaviour of timber elements loaded in different directions. At the scale of structural elements, wood can be assumed to be orthotropic, because the principal directions of anisotropy coincide with the *longitudinal* direction (mostly *parallel to the grain* and the stem), and the *radial* and *tangential* anatomical directions (mostly *perpendicular to the grain*).

Given the significant difference between the stiffness properties in the longitudinal and in the transversal directions (about one order of magnitude), a further common simplification regarding the mechanical behaviour of structural timber elements is to assume that wood is transversely isotropic, i.e. that the stiffness properties are the same in any direction perpendicular to the longitudinal *parallel-to-the-grain* direction. Regarding strength, wood also displays a strong direction dependency, exhibiting lower strengths in the direction perpendicular to the grain than parallel to the grain. The constitutive behaviour of structural timber members is also noticeably different in different directions, exhibiting significant deformations under compressive stresses in the direction perpendicular to the grain and a brittle behaviour under tensile stresses in the direction perpendicular to the grain. Moisture-induced deformations in the directions perpendicular to the grain are 5-10 times larger than parallel to grain (Thelandersson and Larsen 2003).

Failures in timber structures are often associated with the anisotropy of wood, in particular stresses perpendicular to grain (Früwald et al. 2007).

3.2 High variability of physical and mechanical properties

Because of its natural origin, the physical and mechanical properties of timber frequently exhibit a high variability. This variability occurs not only between different elements, but also within the same structural element, due to the semi-random occurrence of various anatomical features that influence the physical and mechanical properties along the stem. The influence of the specific anatomical features (e.g. knots, slope of grain, reaction wood), usually called *defects*, on the physical and mechanical properties of timber depends on several factors, namely the wood species, the relative *size* of the defect, and the position in which occurs in relation to the applied stresses.

To overcome its inherent high variability, timber for structural applications is *graded* and assigned to *classes* or *grades* that try to assure a range of mechanical properties. Nevertheless, since grading procedures for structural timber are mostly concerned with guaranteeing minimum stiffness and strength properties, the variability of physical and mechanical properties between members can be quite significant.

3.3 Moisture and temperature dependency

The mechanical properties of wood exhibit a strong moisture and temperature dependency. If the influence of temperature can be mostly neglected under normal service conditions, i.e. not under fire exposure, the influence of moisture content can certainly not. The moisture content (weight of water in relation to weight of dry wood) of a timber element changes towards equilibrium with the relative humidity of the surrounding air. The response of a timber member to changes in the surrounding climate is slower for larger members and, as a consequence, moisture gradients can develop and cause moisture-induced stresses. These stresses are mostly negligible in the direction parallel to the grain, in which the strains caused by moisture changes are smaller and the strengths are also higher, but can easily lead to failures in the direction perpendicular to the grain, in which the strains caused by moisture changes are higher (5-10 times larger, according to Thelandersson and Larsen (2003)) and the strengths are much smaller. Under normal service conditions, both strength and stiffness decrease with increasing moisture content.

3.4 Low stiffness

As already mentioned, wood exhibits a significant difference between the stiffness properties in the longitudinal and in the transversal directions: the stiffness in the direction perpendicular to the grain is about one order of magnitude lower than in the direction parallel to the grain. Under compression perpendicular to grain, wood displays significant deformations even for low load levels. Whereas a actual mechanical failure in compression perpendicular to grain might only occur for extremely high deformations, imposing such displacements on a structure can cause severe damages elsewhere and is a common source of serviceability failures in timber structures.

Structural timber connections, even those with metallic dowel-type fasteners loaded in shear, are known to exhibit low stiffnesses. If not accounted for during design, this can influence the load paths and induce large displacements. Due to the restraints posed by stiffer elements such as steel plates, cracks due to shrinkage of the timber member can develop in the connection area, reducing the stiffness of the connection even more.

Another stiffness-related aspect of structural timber members subjected to bending by shear forces is the significant level of shear deformations (5 and 20% of the flexural value for beam height to span ratios between 0.1 and 0.05, according to Porteous and Kermani (2013)), due to the high ratio between the modulus of elasticity in the direction parallel to the grain and the shear modulus.

3.5 Duration of load effects

Timber structural elements exhibit a severe strength reduction under sustained loading. Duration of load effects depended on the type of loading, but the longer the duration of loading, the greater the strength reduction. The strength reduction after ten years of loading can be as low as 40% for solid timber and 80% for some wood-based panel (Thelandersson and Larsen 2003). Duration of load effects also depended on the moisture variations that the member is exposed to, with small dimension elements, which are exposed to more moisture variations, exhibiting reduced times to failure.

3.6 Creep

A loaded structural timber member will exhibit an instantaneous elastic deformation followed by a visco-elastic deformation, commonly referred to as *creep* deformation. The magnitude of the creep deformation depends on the combined effects of load duration, stress level, moisture content, and temperature (mostly negligible under normal service conditions). For structural timber members, the creep rate increases with the stress level, but slows down and stabilises if the applied loads remain within the levels corresponding to serviceability limit states. For higher load levels, the reduction of strength due to duration of load effects usually governs the design and creep deformations become relatively less relevant (Porteous and Kermani 2009). Creep deformations increase with moisture content and are higher for cyclic moisture changes, with greater moisture amplitudes leading to higher amounts of creep (Dinwoodie 2000). Creep is also direction-dependent, with greater creep being observed in the direction perpendicular to the grain than in the directions parallel to the grain, for wood under tensile stresses (Dinwoodie 2000).

4. NDT methods – principles and instrumentation

NDT methods allow examining materials or components in ways that do not impair serviceability and future usefulness in order to detect, locate, measure and evaluate flaws, to assess integrity, properties and composition, and to measure geometrical characteristics (ASTM E1316*)*.

A broad variety of NDT methods has been developed and applied to wood and structural timber (Bucur 2003; Kasal and Tannert 2010). However, not all NDT methods can be efficiently used for monitoring purposes (e.g. load testing, or methods involving non-refracting radiation) (Table 2).

Table 2. Applicable NDT methods for determining physical parameters, material states and damages in timber (based on Kurz and Boller 2015). The fields marked with an “x” identify methods that have already been applied.

Methods	Physical parameters, material states, or degradations									
	MOE	Density	Moisture	Inhomogeneity	Cracks	Decay	Failure	Deformation	Stiffness	Dynamical properties
Ultrasound	x	x		x	x	x				
Acoustic emission				x	x		x			
X-ray		x		x						
Thermography				x	x	x	x			
Microwave		x	x	x						
Resistivity			x							
Conductivity		x	x	x						
Nuclear Magnetic Resonance (NMR)		x	x							
Laser optical								x		
Visual				x	x	x	x	x		
Drilling		x								
Quasi-static testing	x								x	
Ambient vibration	x									x
Forced vibration	x									x

To be used in a SHM system, a NDT method must not only be able to continuously and reliably assess a specified property or parameter (e.g. exhibit reduced hysteresis errors, be able to operate under varying environmental conditions), but also comply with various operational requirements (e.g. limited space or power sources). Depending on whether an SHM system is deployed in a new or an existing structure, different requirements may apply.

In this section, the fundamentals of selected NDT methods, applicable to the SHM of timber structures, are presented and their advantages and shortcomings are discussed. They are also analysed considering the damage assessment levels presented in Table 1 (*existence*, *location*, *type*, *extent*, and *consequence*). Regarding this aspect, it is important to keep in mind that the range of NDT methods can vary greatly, from very local (e.g. ultrasonic methods) to global (e.g. vibration-based methods).

Local NDT methods should be able to identify and quantify the extent of the damage, but must be deployed near the "hot spots" of the structure, which means that the *location* of the damage must be known in advance. *Global* NDT methods do not required the sensors to be located close to the damaged area, but are usually less sensitive and the correlation between measurement and damage is not always straightforward.

4.1 Acoustic methods

Acoustic methods are based on the propagation of stress waves (a.k.a elastic waves, or sonic stress waves) through the structural elements and have for long been used in the characterisation of timber and wood-based elements (Bucur 2006; Kasal and Tannert 2010), namely for detecting the onset of failure (e.g. by analysing acoustic emissions), for detecting discontinuities (e.g. detection of cracks and delaminations through ultrasonic methods), and to estimate mechanical and physical properties based on empirical relationships between them and stress wave characteristics (e.g. estimation of static modulus of elasticity based on the wave velocity).

There are two main acoustic methods: analysis of acoustic emissions and ultrasonic methods. The former is a passive method, as it relies on naturally occurring stress waves generated by an internal failure, and the latter is an active method, in which predefined stress waves are induced on the monitored element.

4.1.1 Acoustic emissions (AE)

Principles

An acoustic emission (AE) is a transient elastic wave naturally generated by the rapid release of elastic energy from localized sources within a material (ASTM E1316). NDT methods based on the analysis of signals generated by acoustic emissions are particularly suited to the detection and location of cracking and fractures inside structural elements (Wadley 1986; Bucur 2006). These methods can be integrated in passive monitoring systems, since the energy is released from within the monitored element, rather than it being intentionally exposed to imposed acoustic signals.

Monitoring of acoustic emissions has been mostly used to study the behaviour of small-scale wood specimens (Ansell 1982; Niemz and Lühmann 1992; Aicher et al. 2001; Baensch 2015; Diakhate et al. 2017), but more recently also of structural-sized timber elements (Rescalvo et al. 2018). Depending on the number and characteristics of the sensors and their distances to the possible source of acoustic emissions, the detection volume can cover the whole test specimen (Baensch 2015) and be used to locate the source of the acoustic emission by measuring its arrival time by different sensors (Bucur 2006).

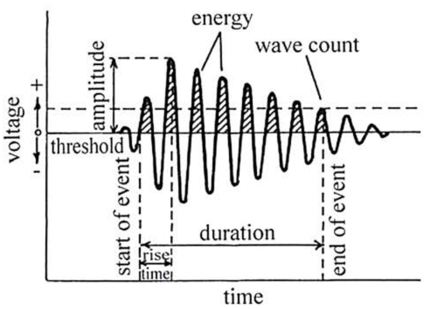
Instrumentation

The main requirements of an acoustic emission system are to be able to discriminate AE signals from background noise and to produce data suitable for comparison with previous and future measurements (Bucur 2006).

Acoustic emissions are usually discrete burst signals generated inside the structural elements (Figure 2), e.g. due to micro-cracking, and the stress wave then propagates to the surface, where they can be detected by appropriate sensors (Nor 2018). The selection of a sensor must consider the specific application conditions, namely the level of acoustic activity in the tested element, the background noise, and the signal attenuation (Bucur 2006; Gautschi 2002). Since acoustic emissions usually exhibit high frequencies (above 50 kHz), piezoelectric sensors are generally used (Kawamoto and Williams 2002), but accelerometers and fibre-optic interferometers have also been used (Ansari 2005). Having a preamplifier near the sensors is also common, due to the low amplitude of acoustic emissions. Signal processors and a computer for data storage and signal analysis are also needed (Figure 3) (Bucur 2006; Rescalvo et al. 2018). The configuration of the system depends on various factors, namely if the location of the source of the acoustic emissions is known in advance (as in small-scale laboratory tests) and the surrounding environmental noise. For a material with high attenuation, such as wood, low resonant AE transducers should be used (Kawamoto and Williams 2002). Also the sensitivity and frequency response of the AE sensor should be considered (Kawamoto and Williams 2002), because an inappropriate transducer in frequency response could modify the acoustic wave considerably (Bucur 2006).

Advantages and disadvantages

The main advantage of AE methods is their ability to detect damage at a very early stage. The main disadvantage is the practical difficulty of implementing such methods in structural-sized elements, due to the required instrumentation and difficulty in discerning the AE signals from the background noise.



Acoustic emission parameters	Type of information carried
Waveform	Fine structure of source event
Frequency spectrum	Nature of source event, integrity of specimen
Amplitude	Energy of source event
Amplitude distribution	Type of damage occurring
Rate	Rate of damage occurring
Distribution time	Type of damage
Relative arrival time at several transducers	Source location

Figure 2. Parameters related to acoustic emission signals (adapted from Bucur (2006)).

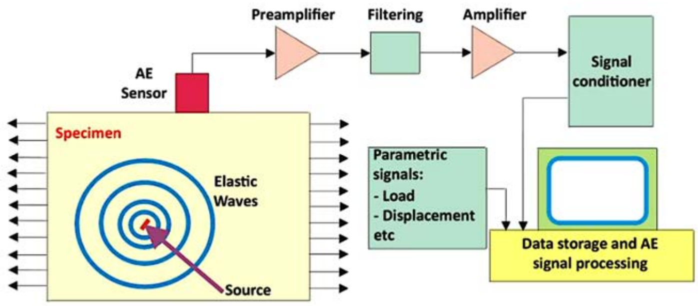


Figure 3. Acoustic emission system (Rescalvo et al. 2018).

4.1.2 Ultrasonic methods

Principles

Sonic and ultrasonic methods use induced stress waves to detect and assess diffuse defect states, damage conditions, and variations of mechanical properties (ASTM E1316). They usually rely on an actuator that generates the stress waves and a sensor that detects them. Since some wave characteristics (e.g. propagation speed, attenuation) vary with the properties and geometry of the propagation medium, signal analysis can be used to estimate material properties (e.g. modulus of elasticity) or detect discontinuities (e.g. through reduced signal transmission) deep inside the elements.

Ultrasonic methods can also be used as imaging techniques (e.g. ultrasonic tomography), to provide a picture of the discontinuity, by combining measurements made in different directions, but these are hardly compatible with SHM systems (Bucur 2006).

Instrumentation

Sonic stress waves can be generated by the mechanical impact of a hammer or by broadband ultrasonic actuators (i.e. that have a wide frequency range), namely made from piezoelectric material (Kasal et al. 2010). A sensor (usually an accelerometer) is required to detect the wave, which can then be analysed. The actuator and the sensor can be positioned on opposing surfaces or on the same surface (even in the same piece of equipment, as in the ultrasonic echo technique), but each configuration and propagation medium requires a specific calibration (Figure 4).

A very important aspect of ultrasonic methods is the coupling conditions between the actuators and sensors and the surface of element. The measurement reproducibility is highly dependent on the coupling pressure, the roughness, and the alignment between the transducers and the surface (Kawamoto and Williams 2002; Kasal et al. 2010). Therefore, the transducers are usually pressed onto the surface using constant weights or springs, and a couplant (either an elastomeric material or a gel) is used to enhance sound transmission (Sanabria 2012).

Non-contact ultrasonic methods (a.k.a. air-coupled methods), which do not need to be in contact with the surface of the material to transmit the stress waves (i.e. use air as a couplant), have also been developed and used in industrial applications, namely production of wood-based plates (fibre and particleboards, and laminated veneer lumber). More recently, a computerized scanning system using non-contact methods was developed to inspect glued laminated timber elements up to 280 mm thick, using off-the-shelf 120 kHz ultrasound transducers and denoising signal processing (Sanabria 2012). This system was able to detect, locate, and assess the extension of delaminations between the timber lamellas. It might not be suitable for SHM applications, but it could be used in manufacturing plants, for quality control.

Advantages and disadvantages

The main advantages of ultrasonic methods are the possibility to detect internal damage or flaws over significant volumes, and the ease of use of the corresponding equipment. The main disadvantages are the influence of the surface preparation and the difficulty of interpreting the results, namely in irregular and non-homogeneous elements.

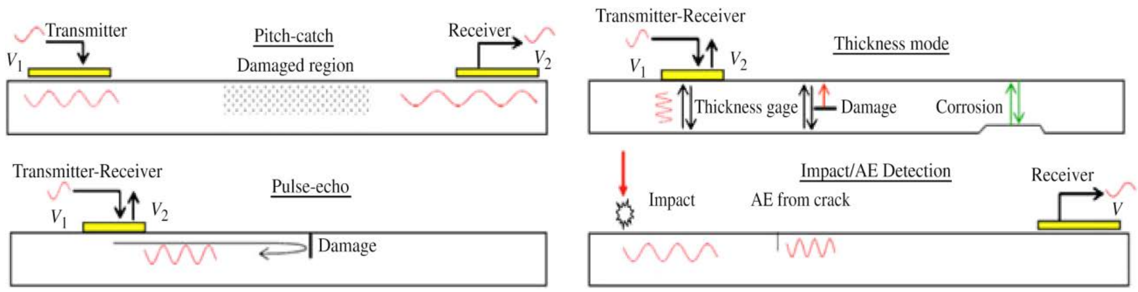


Figure 4. Examples of ultrasonic test configurations (Büyüköztürk et al. 2013).

4.2 Vibration-based methods

Principles

Vibration-based methods assume that damaged-induced changes in stiffness, mass or energy dissipation characteristics can be assessed via the dynamic response of the structure or structural element. Therefore, damage detection requires the identification of data features (e.g. modal frequencies) that allow distinguishing between damaged and undamaged states. The most common features used in vibration-based methods are modal frequencies and mode shape vectors, identified from measured response time histories (usually acceleration), or spectra of these time histories (Farrar et al. 2001).

Many NDT methods have a limited spatial reach and require that the area where damage is likely to occur is know in advance. Vibration-based methods are one of the few that are able to monitor global changes in the structure (Farrar et al. 2001). However, for large structures, the lower modal frequencies, which are typically measured during vibration tests, are less sensitive to damage and may not be enough to identify and locate the damage (not to mention the difficulties in making accurate and repeatable vibration measurements in situ). Higher modal frequencies, usually associated with local responses, could be used to locate damage, but are more difficult to measure and identify. The insight given by this approach, regarding damage *existence*, *location*, *type*, and *extent* (Table 1), depends on the correlation between the real damage and the model parameters. In most cases, pure signal analysis only fulfils the *existence* level; higher levels require additional information. Mode-shape vectors, unlike modal frequencies, are better at locating damage, however they require more sensors to be accurately characterised. Another strategy used with vibration-based methods is to update a numerical model of the structure, so that it fits the structure's response to a given excitation. This approach requires that the correlation between the model parameters and the damage is known. It is therefore not uncommon that preliminary tests on damaged specimens are performed (Choi et al. 2007).

Instrumentation

The standard approach to assess the dynamic behaviour of a structure is to install sensors, excite it with an actuator (or use ambient excitation), and analyse the data (Balageas et al. 2006).

The most common sensors in vibration testing are accelerometers. The main types of accelerometers are: piezoelectric, piezoresistive, capacitive, and force-balance. Piezoelectric-type accelerometers are very robust and stable in long-term use, but their lower frequency limit is usually above 1 Hz, which might be too high for structures with very low frequencies. Piezoresistive and capacitive accelerometers are appropriate for flexible structures, which require low-level vibration measurements. Force-balance accelerometers are suited for low-frequency and low-amplitude acceleration measurements (Xu and He 2017), but are relatively large and heavy and consume more power (Huston 2010).

Various types of actuators are used to impose *forced vibrations* on a structure. Impact hammers and drop weights are typical actuators and they can to some extent simulate an impulse with a very short duration, which results in all modes of vibration being excited with equal energy. However, an impact hammer is hardly compatible with automated SHM systems. A shaker, on other hand, is an actuator that applies a given load to the structure, with a certain frequency, during a predefined period. For building structures, the most common are rotating mass shakers, electro-dynamic shakers, and electro-hydraulic shakers. Depending on the load to be applied to the structure, the weight of the shaker, namely its oscillating mass, will vary from 1-10 to more than 100 kilos. The shaker is attached to the structure and usually operated in sine sweep mode, i.e. continuously sweeping from low to high excitation frequencies (Leyder et al. 2017).

Ambient vibrations generated by local atmospheric conditions or human activities can also, in some cases, be used to characterise the dynamic behaviour of a structure excited by low amplitude vibrations. Operationally, this is the easiest way to excite a structure, because no actuators are required, and is therefore particularly suited for SHM. However, it requires special modal parameter identification techniques that can deal with small magnitude ambient vibration, contaminated by noise, without knowledge of the input forces (Xu and He 2017). These techniques assume that the excitation is a white noise process, which requires that measurements are taken over relatively long periods, so that wider frequency components are included in the excitation.

Advantages and disadvantages

The advantage of vibration-based methods is the possibility of eventually detecting damage through global changes in the structure, even based on ambient excitations. The main disadvantages are the high number of sensors required to locate the damage which may be causing the changes in the dynamical properties of the structure, and the difficulties in extracting relevant data based on ambient excitations.

4.3 Optic methods

Optic methods allow contact-free determination of displacements, surface deformations, and even vibrations (Berkovic and Shafir 2012). These methods have a large variety of uses, including measuring over very long distances (e.g. displacements in bridges) and very short distances (e.g. surface strains and cracks on structural elements), and comprise a wide range of global (e.g. topographic surveying) and local techniques (e.g. digital image analysis). Global techniques can be used to assess damage that has an impact on the deformation of the structure (e.g. support settlements, creep), whereas local methods are limited to defects that reach the surface of the members or, at least, significantly influence surface strains (e.g. cracks).

4.3.1 Classical topographic surveying methods

Principles

Classical topographic surveying methods use the principles and instruments of geodetic surveying to measure angles and distances to target pointy, and therefore their relative coordinates. These methods are commonly used for structural monitoring purposes, namely to determine relative displacements of selected target points, on the surface of the structure, to reference points that are assumed to be stable.

Instrumentation

A total station is an electronic-optical instrument that allows determining the coordinates of a target within direct line of sight, either relative to another point with know coordinates or to the total station itself. Because displacement monitoring frequently requires repeated surveys of the same points, a computer-controlled *robotic total station* can be programmed to automatically perform predefined measurements according to a predetermined schedule. The measurement accuracy of robotic total stations depends on the type of target (geodetic prisms offer higher accuracies than other reflective target systems) and the environmental conditions (which affect the signal used to measure the distance), accuracy of total stations is up to ± 0.1-0.2 mm at close range, i.e. less than 50 m. The measurement frequency depends on the number of target points to be surveyed, since the total station uses servomotors combined with automatic target recognition systems to align itself with the measurement targets. For most practical conditions, the measurement frequencies of robotic total stations are below 0.5 Hz (i.e. more than 2 s per measurement), which is enough to assess short term displacements (e.g. during a load test).

Image-assisted robotic total stations have an image sensor integrated in the telescope, which allows observing natural features or simple non-reflective targets on the object at greater distances. Feature-matching algorithms then track these natural features or targets (e.g. with well-defined edges or patterns that can be easily detected by the algorithms) and compute their new coordinates. There are total stations capable of performing *reflectorless* electronic distance measurements, i.e. using directly the surface of the object as a reflective surface without using a special target, but they might not be adequate if low accuracy tolerances are required (Coaker 2009, Hope and Dawe 2015). From an SHM perspective, the main problem of these systems, is the behaviour of the feature-tracking algorithms under changing environmental conditions, therefore active LED targets are often used (Wagner et al.

2013, 2016). The accuracy of image-assisted robotic total stations is reported to be 0.5 mm at 100 m, but under outdoor conditions it can be 1.6 to 3.1 mm at 100 m (Wagner et al. 2013).

Using highly optimised image-assisted total station under well-controlled in-situ conditions, measurement frequency can be as high as 20 Hz, which is enough for vibration monitoring (Walser 2004; Ehrhart and Lienhart 2015; Wagner et al. 2016). A similar system named *QDaedalus*, developed at ETH Zurich, was able to monitor sub-mm displacements of a prototype beam and estimate its modal frequencies up to 30 Hz (Charalampous 2015).

Advantages and disadvantages

The main advantages of classic topographic surveying methods are that they are reliable, can provide very accurate results, and might not require direct access to the structure. The main disadvantages are the need of a direct line of sight to the target, the dependence on lighting conditions, and the high cost of the equipment, which is then too expensive to be used in long-term monitoring systems.

4.3.2 Terrestrial laser scanning (TLS)[1]

Principles

Current terrestrial laser scanning (TLS) systems are the consequence of the continuous development of total stations (Sub-section 4.3.1), namely the introduction of laser-based reflectorless distance measurements. TLS systems are equipped with laser-based distance measurement devices and can collect large volumes of 3D data (point clouds), with relatively modest data processing requirements. The resolution and accuracy of the point cloud generated by TLS depends on the sampling interval and the laser beamwidth (Lichti and Jamtsho 2006), the incidence angle, the surface characteristics, and the distance to the target. Depending on the scanned object, several scans made from different locations may have to be performed, which are afterwards combined using common reference points. This procedure, however, is not compatible with automated SHM.

Laser scanning has been mostly used to generate 3D models of existing constructions, namely historic buildings and tunnels, but recently it has also been used to asses deformations and, to some extent, damage in structural elements (Park et al. 2007; Vezočnik et al. 2009; Olsen et al. 2010; Mukupa et al. 2017; Law et al. 2018).

Instrumentation

A TLS is usually a tripod-mounted equipment. The principle of 3D coordinate extraction with a laser-based distance measurement device is either based on the time-of-flight measurement of a laser pulse or on the phase comparison between a transmitted and a reflected continuous laser beam (Shan and Toth 2018). The accuracy of the point clouds generated by TLS scans is usually not good enough to assess structural deformations, ranging "from centimetre to millimetre (Mukupa et al. 2017), depending on the scanner, measurement set-up and environmental conditions, and the method of point cloud data processing employed for deformation analysis (Mukupa et al. 2017). There are various

1 As opposed to *airborne* and *spaceborn laser scanning*, which consists in the measurement of terrain elevations from air or spaceborne platforms, using laser profiling techniques.

TLS point cloud processing methods (Park et al. 2007; Mukupa et al. 2017). Typical methods involve modelling the point clouds obtained at different stages, by fitting functions or surfaces (e.g. planes, or lines defined by the intersection of two planes) to predefined areas of the point cloud (e.g. bottom and side surface of a structural beam) and comparing the distances between them.

Advantages and disadvantages
The main advantages of TLS are the independence of natural light sources and no direct access to the structure is required. The main disadvantages are cost of the equipment and the relatively lower accuracy of TLS compared to other methods.

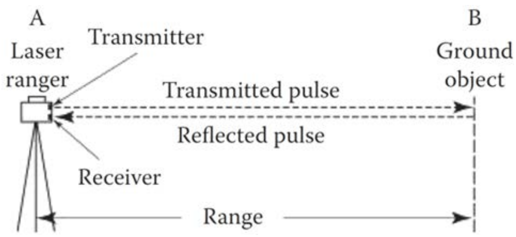


Figure 5. Basic operation of a laser rangefinder that is using the timed pulse or TOF method (Shan and Toth 2018).

4.3.3 Photogrammetric methods

Principles
Photogrammetric methods are based on extracting geometric measurements from two-dimensional digital images, through adequate image-analysis techniques. These methods comprise obtaining an image of the surface of the object, storing that image in digital format, and running image analysis algorithms to extract deformation and/or motion measurements. Photogrammetric methods can be applied to very small to and very large objects (e.g. cracks in small scale test specimens and displacements in bridges) (Maas and Hampel 2006).

Signalized target measurement techniques involve placing discrete targets on the surface of the monitored elements and then tracking these points in consecutive images. This can significantly simplify the data processing, if suitable illumination techniques are used, and can be achieved with commercial photogrammetric measurement systems (Maas and Hampel 2006). These techniques are used to measure the displacements of the targets. *Image-matching techniques* use natural or artificial surface texture (e.g. a speckle pattern) to track areas in consecutive images. These techniques require significant more complex image-analysis algorithms, but are able to deliver full-field measurements, namely surface strain fields, in the observed areas. Cross-correlation is a specific image-analysis technique, but the increasingly popular name *digital image correlation* or *DIC* is sometimes used to refer to all image-matching techniques, not only those based on cross-correlation.

Regarding structural monitoring, photogrammetric methods have been used to measure displacements (Henke et al. 2015; Maas and Hampel 2006; Valença et al. 2011), surface strain fields in critical components (Winkler and Hendy 2017), and even vibrations in cables in cable-stayed bridges (Zhou et al. 2012).

Instrumentation
Photogrammetric methods require a digital camera (or more, for 3D measurements) and hardware to store and analyse the obtained images. These digital cameras were often equipped with CCD sensors (Sutton et al. 2009), but cameras with CMOS sensors are becoming more common (Henke et al. 2015). When discrete targets are used, these are either easily distinguishable, to facilitate the image analysis, or have integrated LEDs, which also allow for measurements to be taken at night. LEDs emitting in the infrared range have also been used, to avoid interferences from other light sources, but the cameras must then be equipped with adequate filters (Henke et al. 2015).

Photogrammetric methods have been used for deformation monitoring in bridges, most of which reaching accuracies of about 1 mm (Jiang et al. 2008). Local monitoring of bridge components using 2D-DIC systems has also been used to evaluate strains (Winkler and Hendy 2017), but the errors of in situ measurements are potentially too large, because of the small strains expected under service loads and the high uncertainties regarding the measurement conditions (Hoult et al. 2013).

Advantages and disadvantages
The main advantages of photogrammetric methods are that direct access to the structure may not be required, the large amount of information recorded in a short time period, and the possibility of using lower-cost components than TLS or classic topographic surveying methods. The disadvantages of photogrammetric methods are the lower accuracy compared to classic topographic surveying methods, the usually complex image-analysis techniques required to extract relevant measurements, which often requires careful calibration.

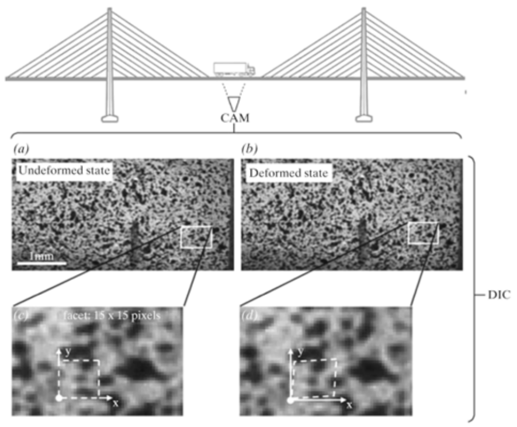


Figure 6. Digital image correlation method (Winkler and Hendy 2017).

4.4 Fibre-optic-based methods

Principles
Fibre-optic sensor technology uses light to conduct measurement of physical properties in remote sensing applications. Fibre optic sensors are based on modifying an optic fibre so that the property or condition being measured modifies the characteristics (intensity, phase, polarisation and wavelength) of light in the fibre (Xu and He 2017).

Current fibre-optic sensors are mostly wavelength or frequency-based, which includes fibre Bragg gratings (FBG) (Karbhari and Ansari 2009). FBG-based sensors have been popularised and used to directly measure strain and temperature, even though they can also indirectly measure other properties by measuring the induced strain. The periodic gratings inscribed in the fibre reflect the only a specific wavelength and straining or heating the fibre changes this wavelength, as well as other properties (Berkovic and Shafir 2012).

Instrumentation

Optic fibres can serve as both sensor and signal transmission medium, which allows having the instrumentation located away from the measurement locations (Karbhari and Ansari 2009). Several fibre-optic sensors can be inscribed in the same fibre (multiplexing), allowing for simultaneous distributed sensing over large distances, using a single channel, with measurement frequencies up to thousands of Hertz (making them suitable for dynamic measurements). One optic fibre can accommodate up to 6-10 FBG sensors (Xu and He 2017). Optic fibres are typically 0.25 mm in diameter and rather fragile, requiring careful handling during installation. The fibres are not vulnerable to electromagnetic interferences and less sensitive to vibrations or heat than traditional gauges. They also do not need often recalibration, being quite immune to ageing. FBG sensors typically exhibit strain resolutions of 10 microstrains (Berkovic and Shafir 2012). FBG sensors are affected by temperature variations, which should be appropriately accounted for, e.g. by including an additional parallel cable that exclusively measures the wavelength variations due to temperature.

Advantages and disadvantages

The advantages of using fibre-optics sensors are the possibility of adapting to measure various parameters, the possibility of having multiple sensors in a single optic fibre, their resistance to harsher environments, and their ability to be used for high-frequency measurements. The possibility of having multiple sensors in the same cable can allow detecting and locating the damage. The disadvantages are the high cost of producing the sensors and of the data acquisition instrumentation and the general lack of knowledge on how to install use these sensors, e.g. in comparison with traditional strain sensors.

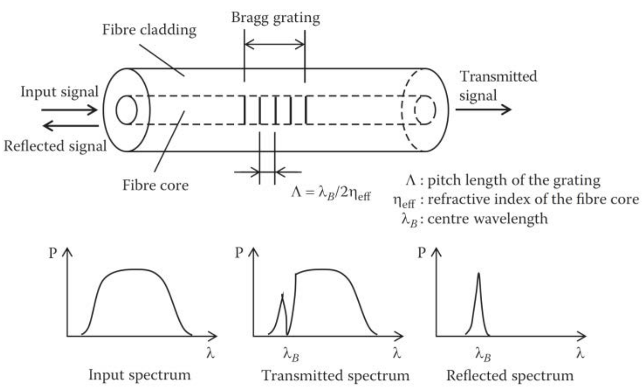


Figure 7. Principle of operation of an FBG sensor (Xu and He 2017).

5. Parameters of interest and monitoring techniques for timber structures

According to Mufti et al. (2001), the first part of a SHM system usually involves the measurement of: strains, deformations, accelerations, temperatures, moisture, acoustic emissions, time, load, or other attributes of a structure. In the following sections, relevant properties and parameters regarding the monitoring of timber structures and the corresponding monitoring techniques are presented and discussed.

Some timber properties that are of extreme importance in some contexts (e.g. modulus of elasticity, density, inhomogeneities) are not so relevant for SHM purposes. From a SHM perspective, it might not be so interesting to obtain accurate estimations of the absolute values of these properties, but to be able to detect *changes* in these properties with adequate precision. Accurate estimations of the modulus of elasticity (MOE) of timber members is not so interesting from a SHM perspective. It can be relevant to estimate the MOE for structural assessment purposes (e.g. in situ assessment of the mechanical properties of a structural member), or from a production quality control perspective (e.g. strength grading of timber boards). Changes in stiffness, on the other hand, are relevant for SHM purposes, as they can serve as a proxy for damage. However, NDT techniques that can be used to *accurately* estimate the MOE (e.g. propagation of an ultrasonic wave along the wood fibres (Sandoz 1989)) might not be usable in the context of SHM, due to lack of precision or because they provide only very localised information. Accurate estimations of density are also not relevant from a SHM perspective, only for structural assessment purposes (e.g. to estimate strength) or production quality control perspective (e.g. strength grading of timber). Changes in the density of timber structural elements are also not expected to occur under normal service conditions. The monitoring of displacements/deformations has no particular specificities in the case of timber structures and common monitoring techniques used in other contexts can also be directly implemented. Even though pilot projects on novel monitoring strategies have been incidentally conducted on timber structures (e.g. based on digital imaging analysis (Henke et al. 2015)), they were in no way restricted or particularly adapted to timber structures. Displacements are, nevertheless, of extreme importance in timber structures, since deformation rather than strength is commonly the limiting factor in the design (Porteous and Kermani 2009). The specific aspects regarding displacements in timber structures which should be accounted for when developing a monitoring system are: periodic seasonal variations due to moisture content fluctuations; settlements in areas where timber members are under localised compression in the direction perpendicular to the grain; and creep-related displacements (dependent on the stress level, the duration of loading, and the moisture content). Monitoring of loads has also not specificities regarding timber structures. Specific sensors for traffic or snow loads are available and can be used in timber structures.

The Swiss standard for the design of timber structures (SIA 265:2012) provides some guidance regarding monitoring. In particular, it requires: that "if a structure or a component requires special monitoring or maintenance measures, the manufacturers have to provide written instructions or rules when the structure is put into service"; "changes in use, depending on the new type of use, require a new monitoring programme"; "in the case of prestressed structures, the loss of stress over time has to be monitored"; and "when monitoring deformations, in addition to the members in bending, the deflection of members in compression (e.g. compression chords in trusses) or of structural systems (e.g. frames) shall be taken into account".

5.1 Moisture content

Prevalent damages in timber structures are related to the moisture content of wood (Früwald et al. 2007; Blaß and Frese 2010). Sustained exposure to ambient conditions that lead to moisture content levels above 20% can lead to damage by wood-decay fungi or subterranean termites, whereas in-service drying can cause the development of cracks. A review of indirect methods to assess the moisture content of wood is presented by Dietsch et al. (2015a). These methods are based on the measurement of physical properties that, amongst other parameters, are also dependent on the moisture content.

Electrical resistance method

The most commonly used method for monitoring purposes is based on measuring the electrical resistance of wood. Given that water has a much higher electrical conductivity than wood, the conductivity of wood increases with increasing moisture content. The relationship between the electrical resistance of wood and its moisture content is logarithmic: approximately 10000 MΩ for moisture contents between 9 and 10% and 10-100 MΩ for moisture contents between 15 and 20%, for Nordic Pine (*Pinus sylvestris* L,) and Spruce (*Picea abies*, (L.) H. Karst.).

The electrical resistance method uses two electrodes, between which the electrical resistance is measured (Figure 9). This allows assessing the moisture content at predefined depths, by adjusting the penetration depth of the electrodes. However, since the electrical resistance is measured through the path of the least resistance (i.e. with higher moisture content) if there is a significant moisture gradient along the uninsulated length of the electrodes, only the highest value is measured. Measurements depend on the type of electrode and on the contact between the electrodes and wood. For long term measurements, swelling and shrinkage of wood around the electrode can lead to micro cracks, which then allow water to enter through the capillary interstices along the electrode. For this reason, the electrodes should usually not be aligned with the grain (Brischke et al. 2008a).

The conductance/electrical resistance method is adequate for moisture contents between 8 and 24%, which is the expected range for most timber structures. Forsén and Tarvainen (2000) report measurement accuracies of ±1.5-2.5% in laboratory tests and ±2.0-5.0% in industry tests, for hand-held moisture content meters. The electrical resistance of wood is significantly influenced by temperature, decreasing with increasing temperature, and the estimation of moisture content has to take this parameter into account. Therefore, temperature must be measured simultaneously with electrical resistance measurements.

There is some dependency of the electrical resistance on the wood species and also on the presence of water-soluble salts or other electrolytic substances (e.g. from preservative or fire-retardant treatments) and the electrical resistance curves (relationship between measured electrical resistance and moisture content) should be adjusted accordingly. Therefore, electrical resistance method has to be calibrated for each wood species.

Regarding the measuring direction, James (1988) states that the electrical resistance of wood in the direction parallel to the grain is approximately half of that in the direction perpendicular to the grain, however, Forsén and Tarvainen (2000) did not observe any influence of the measuring direction when testing hand-held resistive moisture meters. Therefore, the direction of the electrodes should be consistent with the direction used to derive the electrical resistance curves.

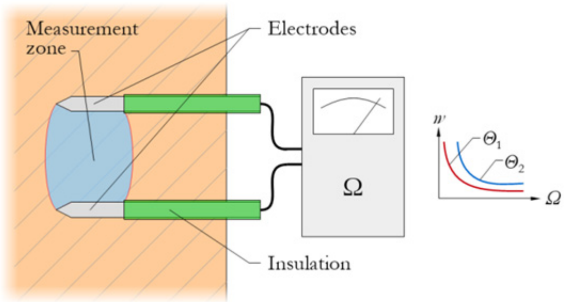


Figure 8. Conductance/electrical resistance method.

Dielectric method

The dielectric method is based on the influence of moisture content on the dielectric properties of wood. The two fundamental types of dielectric moisture meter are the capacitance type meter, based on the relationship between moisture content and the permittivity of wood, and the power-loss type meter, based on the relationship between moisture content and the dielectric loss factor of wood (James 1988). The logarithm of the relative permittivity of wood increases roughly linearly with increasing moisture content and the slope of the relationship increases as the frequency of the applied field decreases. Woods with higher density exhibit a higher increase of relative permittivity for higher moisture contents, because the relative contribution of the cell wall is greater than for the low density woods. Relative permittivity of wood increases with temperature, except at very high moisture content where the reverse can occur (James 1988; Forsén and Tarvainen 2000). The relationship between the loss factor and moisture content is more complex and depends on temperature and frequency of the applied field, exhibiting maximum and minimum values at various combinations of these variables. The loss factor is the product of two quantities that increase with density (relative permittivity and the dissipation factor, the latter commonly referred to as tan δ) and, therefore, also increases with density, at least for lower frequencies. Regarding temperature, the loss factor can both increase and decrease with increasing temperature, depending on the frequency and moisture content (James 1988; Forsén and Tarvainen 2000).

Dielectric-type meters use contact electrodes (i.e. applied only on the surface of wood) and their measurement range is limited in depth (Figure 10), because the electric field generated between the electrodes decreases rapidly with depth of penetration. Therefore, measurements are predominantly influenced by the outer layer. Wood with a significant moisture gradient or a wet surface will give inaccurate results (Forsén and Tarvainen 2000), as will a bad contact between the capacitor plates and the wood surface (which might be difficult for rough surfaces).

The dielectric method is adequate for moisture contents between 5 and 30%. Forsén and Tarvainen (2000) report measurement accuracies of ±2.0-5.0% in laboratory tests and ±3.0-5.0% in industry tests, for hand-held moisture content dielectric-type meters. The measurements of dielectric-type moisture meters must be adjusted for wood density and the high variability of this parameter, even within the same species, can lead to erroneous estimations of the moisture content. In addition, even though species with similar densities have approximate dielectric properties this is not always the case and the correction factors should also be species dependent. The presence of water-soluble salts or other electrolytic substances might also influence the dielectric properties of wood. The electrodes used in dielectric-type meters are designed for each instrument and are not interchangeable between different equipments, as the electrodes for electrical resistance meters.

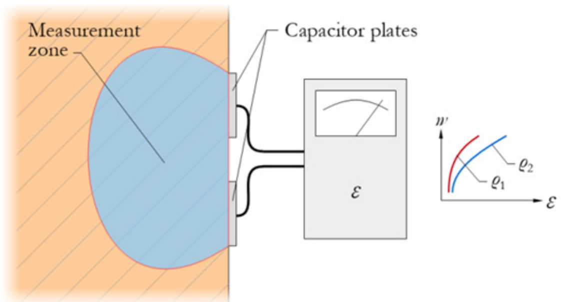


Figure 9. Capacitance/relative permittivity method (open plate capacitor).

Hygrometric method

The hygrometric method is based on the relationship between the equilibrium moisture content of wood and the ambient relative humidity, at constant temperature and steady-state conditions. This relationship is called *moisture sorption isotherm* and exhibits a highly non-linear behaviour, is temperature dependent (the slope of the isotherms decreases with increasing temperature), exhibits hysteresis between adsorption and desorption, and is dependent on the wood species. Due to the complexity of sorption processes, moisture sorption isotherms are determined experimentally.

Based on the temperature and relative humidity measurements of the air in a confined space inside the timber element, the equilibrium moisture content of the surrounding wood is estimated using the corresponding moisture sorption isotherm (Figure 11). This requires the installation of temperature and relative humidity sensors in a small confined cavity, which might be difficult due to the dimensions of relative humidity sensors (common temperature and relative humidity probes have diameters larger than 1 cm). In addition to the size of the sensors, the path through which they are installed must be sealed, to reduce the wood surface that can exchange moisture with the confined volume of air. Given the significant size of the probes and the fact they are made of metal or plastic, if they are positioned too close to the surface, the disruption they cause in moisture transport and the exposure to more transient conditions (moisture sorption isotherms are derived for steady-state conditions) will lead to results which are not representative of the *real* moisture content at those depths.

The widely used relations between ambient temperature and relative humidity and the equilibrium moisture content of wood (Glass and Zelinka 2010), determined by exposing a piece of wood to various steady-state temperature and relative humidity conditions, might not be adequate to estimate the moisture content of wood surrounding a small enclosed cavity (Dyken and Kepp 2010). This seems to be related to the air temperature inside the cavity, which has a high influence in the calculated equilibrium moisture content of wood, but the source of the observed deviations is not completely clear. It could be that heat conduction through the measurement probe induces faster temperature changes in the air inside the cavity than would occur in the wood at the same depth; or that heat builds-up in the sensors during the measurements. Therefore, this measurement method might require a previous calibration under controlled conditions.

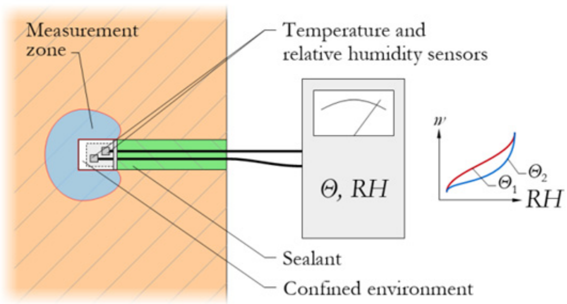


Figure 10. Hygrometric method.

5.2 Biological degradation

Under appropriate conditions, wood can be damaged by bacteria, fungi, algae, insects, marine borers and other biological agents. In Europe, the most common causes of biological degradation are decay-causing fungi, boring insects and marine borers (Reinprecht 2016). Some of these biological agents required damp/wet wood and, therefore, the conditions for their development can be monitored via the moisture content and temperature of wood (Section 5.1). Only beetles, hymenoptera (namely wood wasps and carpenter ants), and dry-wood termites do not required damp or wet wood and, therefore, their activity has to be monitored using other methods.

Pest monitoring techniques have not been implemented in structural monitoring applications, but pest sensors have been developed that could be further developed and integrated in SHM systems.

5.2.1 Wood-decaying fungi

Wood-decaying fungi (brown-, white-, and soft-rot fungi) destroy the main chemical components of wood (cellulose, hemicellulose, and lignin), therefore compromising its physical and mechanical properties (Reinprecht 2016). The development of fungi is mostly controlled by the moisture content of wood: fungal spores require moisture content above the fibre saturation point to germinate (approximately 25-30%) and fungal development requires approximately 20% moisture content or higher, depending on the species of fungi and wood. However, if wood is submerged in water, fungi cannot access oxygen and will not develop. Fungal development also requires temperatures between 10-35 °C (optimum between 24-32 °C) (Ibach 2012). Since it is very likely that spores of wood-rotting fungi will be present wherever wood is used, wood will decay if the conditions to which it is exposed are favourable for fungal growth (Baker 1969). Therefore, an appropriate strategy to monitor the **moisture content** and **temperature** of wood (see section 5.1) is adequate to assess if the structure is at risk of decay. Brischke and Rapp (2010a;b) established *dose-response functions* between moisture content and temperature of wood (*dose*) and fungal decay (*response*) to make service life predictions of small wooden components (fence posts, pickets, and deck boards).

If favourable conditions for fungal grow are maintained, significant strength loss can occur in the early or incipient stage of wood decay (Ibach 2012). Strength loss due to wood-decaying fungi seems to be directly related to changes in chemical composition: the initial strength loss in wood is related to deterioration and loss of the side and main-chain hemicellulose components, followed by deterioration of cellulose and lignin (Winandy and Rowell 2012; Winandy 2017). In small-scale specimens, considerable bending strength loss has been reported to occur before measurable weight loss (strength loss of approximately 40% for a weight loss of 10%). Loss in stiffness increases less rapidly, suggesting that it is related to the cellulose rather than the hemicellulose composition (Winandy and Rowell 2012). However, monitoring of fungal growth in wood requires chemical analyses that are not compatible with SHM systems and, in addition, deriving wood strength from the results of these analyses is not straightforward.

The best NDTs to assess fungal growth in wood are, therefore, through its effects on stiffness and mass. **Ultrasonic methods**, namely transverse transmissions (i.e. waves propagating in the direction perpendicular to the fibres), can be used to map deteriorated regions through *wave velocity*, *wave attenuation*, or *frequency spectrum analysis* (Kasal and Tannert 2010). Wave velocity is highly correlated to the stiffness of wood and slower velocities can be a sign of deterioration, as are higher levels of wave attenuation (R.J. Ross et al. 1997). Stress waves with longer wavelengths are not so sensitive to small defects, since only defects larger than half the wavelength are detected, and are better suited to identify large deteriorated zones. Decayed wood also exhibits lower natural frequencies, which depend on mass and stiffness, and different frequencies are observed depending on the level of deterioration in the member. Even incipient decay, which might not be detected through wave velocity measurements, can be detected through frequency spectrum analyses (Kasal et al. 2010). These assessment methods, however, can be influenced by moisture content gradients in wood and measurements must always be compared to results obtained in sound wood. In addition, multiple stress wave measurement points, on opposite sides of the analysed timber element, are needed to accurately *map* a given area of the timber element (Figure 11).

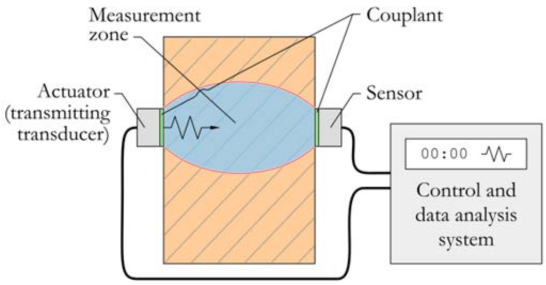


Figure 11. Transverse transmission (acoustic method).

5.2.2 Wood damaged by insects

Acoustic emissions have been successfully used to monitor insect activity in grain and wood, mainly standing trees (Mankin et al. 2011). The main issues with acoustic detection have been related to acoustic signal attenuation and difficulties in identifying weak insect signals in environments with high background noise (Section 5.3.1). Robins et al. (1991) observed that the spectrum of termite-caused acoustic emission signals has substantial ultrasound content (frequencies above approximately 10-20 kHz), with peaks at approximately 50 and 80 kHz. Mankin (2011), citing various studies, states that since wood has a relatively low attenuation coefficient, ultrasound generated from termite activity could be detected up to 2.2 m from the sensor, along the grain. However, given that the attenuation coefficient is about 2-5 times higher in the direction perpendicular to wood fibres, termites could only be detected approximately 8 cm from the sensor across the wood grain.

The most common pest sensors used to detect acoustic signals produced by insects comprise contact *electret* microphones, accelerometers, and piezoelectric sensors. Farr and Chesmore (2007) report that piezoelectric sensors performed better than electret microphones at detecting the presence of wood-boring insects, but electret microphones, due to their greater spectral range, performed better at discriminating between species. These sensors were used alongside with filtering and feature extraction algorithms and trained artificial neural networks.

Optical techniques have also been used to detect termite infestations, based on the variations of reflected light induced by the presence of these insects (Oliver-Villanueva and Abián-Pérez 2013; Perles et al. 2016). The developed pest sensors comprised a light emitter (LED) and a receiver (light sensor), positioned inside a small tube, which is then inserted in a wood element, and through which the termites should eventually pass. The detection algorithms were designed to adapt to changing conditions, such as dust and temperature effects. Both studies used subterranean termites (*Reticulitermes* genus), which exhibit a well-known light-avoidance behaviour and, therefore, built mud tube trails inside the sensors, to shield themselves form the light emitter, rendering the sensors obsolete after some time.

5.3 Delamination and cracks

Delamination (debonding) and longitudinal cracks of timber-based structural members are a recurrent cause of failures in timber structures (Blaß and Frese 2010). Their causes range from underperforming adhesives, to restricted shrinkage, and over-loading. The detection of defective glue lines during production and in structures in service is therefore critical for the structural safety. Delaminations might be difficult to detect by visual inspection, but other NDT detection methods have been developed (Bucur 2011) (Sanabria 2012).

5.3.1 Acoustic methods

Acoustic methods have for long been used to characterise timber and timber-based elements. They are very sensitive to material and mechanical properties and to the presence of defects, such as delaminations and cracks. The equipment used for acoustic testing has usually relatively low costs and small size.

Monitoring of **acoustic emissions** has been mostly used to detect failure in small scale test specimens (Ansell 1982; Aicher et al. 2001; Bucur 2011; Lamy et al. 2015; Diakhate et al. 2017), even though it has also been used in full-scale timber beams (Rescalvo et al. 2018). The results show that AE signals coincide with the onset of failure, even before it can be visually detected, and can be used to detect and locate cracks within timber elements. However, the attenuation of AE signals and the influence of ambient noise requires that the zone where failure is likely to occur is known in advance, or the use of many sensors (Rescalvo et al. 2018), and the use of advanced data processing techniques. Interpreting AE signals is also very much dependent on the experimental conditions and experience of the operator (Bucur 2011). Due to the nature of the source of the signal, reproducibility of test results is also difficult.

Ultrasonic methods, on the other hand, have been widely used to detect cracks and delaminations in timber elements (Bucur and Kazemi-Najafi 2011), since they induce significant changes in the propagation of stress waves. These methods have been traditionally based on discrete point measurements using sensors and actuators that are pressed onto the timber surface with a couplant. These methods have been used successfully used to detect delaminations (Dill-Langer et al. 2005; Divos 2011), but require repetitive and time consuming measurements to go through large elements. The results are also dependent on the coupling between the sensors and actuators and the surface. Depending on the specific method, a single sensor/actuator may be used. Non-contact ultrasonic methods are used in industrial applications, namely the production of wood-based plates, and give a more continuous overview of delaminations and cracks (Bucur and Kazemi-Najafi 2011). The non-contact system developed by Sanabria (2012) allows inspecting glued laminated timber elements up to 280 mm thick.

Acoustic methods are widely used in the assessment of existing structures and, in theory, could also be automated and used in active SHM systems to detect the occurrence of cracks and delaminations in structural members. Sensors and actuators can be installed on structural members in service, or be integrated in them during production (e.g. in glued-laminated timber elements) if the critical zones for cracks and delaminations are known in advance (namely where high shear or perpendicular to the grain stresses are likely to occur). These systems, however, need to be calibrated to each specific application, because of their sensitivity to physical and mechanical properties (e.g. density, stiffness, moisture content) and geometry. Once in place, the system could generate predefined acoustic pulses at selected time intervals and compare the obtained response signals. Such a system would only work if initially there was no damage, or if it was very limited. The long term performance of such system would have to be studied.

5.3.2 Vibration-based methods

The use of vibration-based methods to assess the properties and evaluate the condition of timber elements is basically limited to *transverse vibration* techniques (Ross 2015). These techniques are based on assessing the modal frequencies and damping properties of elements subjected to vibrations perpendicularly to the axis of the element, which are picked up by appropriate sensors, and analysed. The presence of delaminations or cracks changes the dynamic behaviour of the element and this could be detected by changes in the dynamic properties. These techniques have been successful in detecting and locating damage under laboratory conditions (Choi et al. 2007), but are highly dependent on the support conditions of the members, which could change depending on re-tightening of bolts or friction in the connections. In addition, the lower modal frequencies typically measured during vibration tests are less sensitive to damage than higher frequencies, which are more difficult to measure, and the number of sensors required to correctly identify dynamic properties and locate the crack might be quite high. Finally, for stiffer members, the size and power of the actuator (e.g. a shaker) would hardly be compatible with its use in practice, and inducing vibrations in structural elements might have an impact in operational aspects (e.g. loosening of nuts, damage to non-structural components with fundamental frequencies close to the excitation frequency, or discomfort to users).

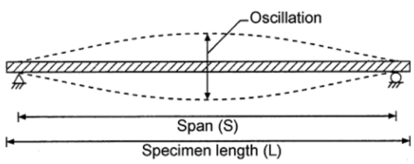


Figure 12. Schematic of typical free transverse vibration test setup (Ross 2015).

5.3.3 Optic methods

Digital image correlation (DIC) analyses have been successfully used to study small-scale specimens (Dubois et al. 2012; Serrano and Enquist 2005), full-scale timber elements (Jockwer 2014; Murata et al. 2005), and even timber-frame buildings (Sieffert et al. 2016). However, given the strict requirements regarding lighting, surface preparation, and system calibration, the use of DIC has been mostly limited to laboratory studies. Integrated in SHM systems, a DIC-based system has been used to monitor strains in the small area around a notch where fatigue cracks were expected to grow, in a riveted steel structure (Winkler and Hendy 2017), but its long term performance is questionable, given the need of repeatable surface and environmental conditions to be able to compare images taken at different stages.

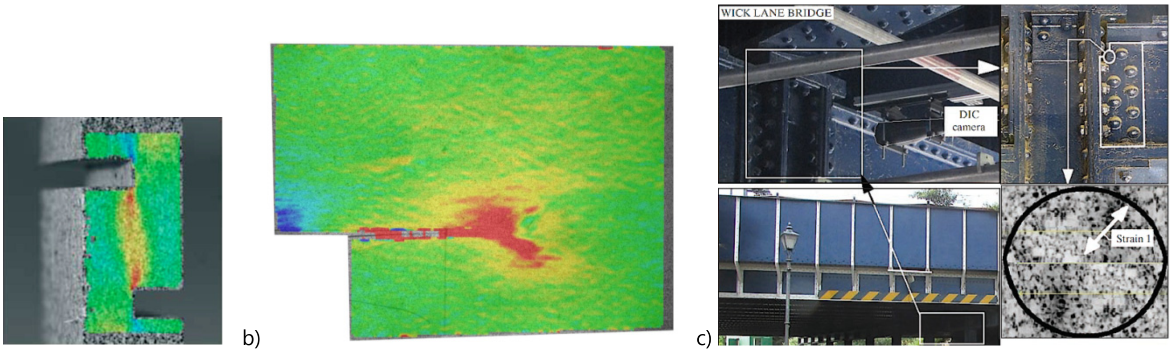
a) b) c)


Figure 13. Strains measured using DIC systems: a) small-scale test specimen (Serrano and Enquist 2005); b) notched support of a full-scale timber beam (Jockwer 2014); c) DIC monitoring system (Winkler and Hendy 2017).

5.3.4 Fibre-optic based methods

Fibre-optic sensors can configured to monitor cracks and have been used in the monitoring of bridge piers during seismic tests and cracks in masonry structure (Karbhari and Ansari 2009). The ends of the arch-shaped sensor are installed of opposite sides of the crack , or where the crack is expected to occur, and the crack width can be inferred from the response of the the sensors. Several sensors can be spliced along a single cable.

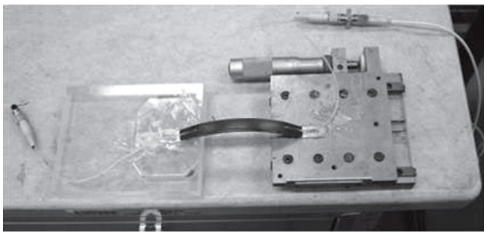


Figure 14. Fiber optic crack (Karbhari and Ansari 2009).

5.3.5 Self-healing strategies

Capsule-based systems used in self-healing materials could also maybe be used to signal the onset of delamination. Microspheres have been been added in very significant quantities to adhesives, without reducing the bonding quality of wood joints (Pinkl et al. 2018; Winkler and Schwarz 2014). This opens the possibility of using spherical particles carrying encapsulated pigments that would be released if the capsules were subjected to a given stress level or delamination occurred. This would not be part of SHM system, but could allow early detection of delamination during visual inspections.

5.4 Deformations and displacements

Deformations and displacements in structural elements and structures are consequences of actions, which can vary in nature (e.g. gravity loads, climatic changes, earthquake-induced accelerations, support settlements, moisture or temperature changes), magnitude (e.g. storage loads, wetting-drying cycles), and duration (e.g. instantaneous wind gusts, permanent self-weight). Timber structures are prone to exhibit problems related with excessive deformations and displacements (see Section 3), namely due to high moisture content, creep (dependent on the stress level, the duration of loading, and the moisture content), low stiffness in the direction perpendicular to the grain (which can problematic close to supports), insufficient stiffness in connections, or high E_0/G ratios that induce non-negligible shear deformations.

Deformations and displacements can be irreversible or reversible, depending on whether they remain, or not, after the corresponding actions are removed. Given the visco-elastic behaviour of wood (Section 3.6), actions with longer durations are prone to cause irreversible deformations and displacements. On the other hand, moisture content fluctuations caused by environmental changes or by shorter-duration loads usually cause reversible temporary deformations and displacements, which might not have significant consequences, as long as they remain within the serviceability limits.

Deformations and displacements have implications mostly in the use of the structure, i.e. serviceability limit states, but they can also be related to ultimate limit states. The requirements concerning serviceability (Lüchinger 1996) are related to: the function of the structure or parts of it under the intended use (e.g. water-tightness, boundary conditions of non-loadbearing elements, ducts or channels of building services); the comfort of users; the appearance of the construction works (i.e. deflections or cracking). A case in which excessive deformations are related to ultimate limit states is the ponding of water on roofs, i.e. local accumulation of water on a roof due to the deformation of the roof structure caused by the weight of the water.

Signalized target measurement techniques, using infra-red LED targets and cameras (Figure 15a,b), which are not affected by the lighting conditions in situ, were used to monitor displacements in a large span timber structure (Henke et al. 2015). The system is reported to measure displacements "with an accuracy in the range of a millimetre" in laboratory tests and maximum errors of 2 mm in displacements of 100 mm, at a distance of 23 m from the target. This monitoring method can be used for all types of structures and it does not need to be in any way adapted for timber structures.

A **laser-based system** was developed by Moore et al. (2011, 2012) and used to monitor vertical displacements in timber bridges under road traffic. The system was installed inside a PVC tube, for protection (Figure 15c), which would not be allow in many cases due to aesthetic reasons (these concerns were also mentioned by some answers to the survey on SHM).

a) b) c)

Figure 15. Optic measurement systems: a) infra-red LED target for photogrammetric-based displacement measurements (Henke et al. 2015); c) laser-based displacement measurement system, inside PVC tube for protection (Moore et al. 2011).

5.5 Strains

The use of “traditional” **resistive strain sensors** is relatively limited in timber-related research. Since these sensors provide a single-point measurement and timber elements exhibit non-uniform anisotropy, spatial non-homogeneity, and high variability, the strain measurements can be misleading and non-representative. In addition, the variability of stiffness properties makes it difficult to estimate stresses based on local strain measurements. Moisture changes in wood can also influence the readings. Therefore, a thorough surface preparation including the application of an epoxy sealant is necessary (Hale and Chapman 2014). Also the low thermal conductivity of wood can cause the strain sensors to overheat and give erroneous measurements. Nevertheless, some authors state that these sensors are less prone to damage than FBG strain sensors, when integrated during the production of glulam members (Pence 2013).

Fibre Bragg grating (FBG) strain sensors are much better suited to measure strains in timber elements (Leyder 2018; Hamann et al. 2013). Their advantages are the ability to have several distributed sensing areas in a single optic fibre and providing strain measurements over longer lengths. These sensors are also more resistant to harsh environments (Bremer et al. 2016) and exhibit long term measurement stability (Hamann et al. 2013) in timber-based elements. FBG sensors can be installed during production of the structural elements (Habel et al. 2014; Hamann et al. 2013; Deza 2011) or with the structural member already in place (Leyder 2018). They have also been successfully used for static and dynamic tests, with sampling frequencies up to 100 Hz (Leyder 2018). Care must be taken to assure that shear stresses in the beam do not induce strains in the FBG sensors, if they are to measure only longitudinal strains due to bending.

The use of Fibre Bragg grating (FBG) strain sensors in timber elements is still relatively new and their installation in timber elements is still being studied (Hamann et al. 2013; Deza 2011). Most of the projects involving strain measurements were done in collaboration with the sensor manufacturers, due to the need of producing specific sensors for each application and the high cost the data acquisition instrumentation. Deza (2011) and Phares et al. (2010) report that FBG sensors were easily damaged when being integrated in glulam beams during production or afterwards, when handling the beams. The long-term beahviour of the FBG strains sensors installed in timber members subjected to fatigue loads, as in bridges, is also unknown.

6. Case studies

Most of the monitoring case studies presented in this section are relatively recent (less than 10 years old). Moisture content is the most commonly monitored parameter, due to its extreme relevance to the behaviour and durability of timber, but also because of the relatively low cost and simplicity of the necessary instrumentation (Section 5.1).

6.1 Moisture content monitoring in Germany and Switzerland

Brischke et al. (2008a; b) developed a long-term moisture content measuring and data logging system, based on measuring the electrical resistance of wood, using glued-in stainless steel electrodes inside pre-drilled holes. The system is reported to have worked for five years without any maintenance. It was also installed in a pedestrian bridge in Germany, where it successfully measured and recorded values for two years. The installation of the glued-in electrodes is problematic if it has to be done from below, which is a disadvantage in comparison with other electrodes such as pins or screws.

A similar system was deployed by Tannert et al. (2011), in a timber bridge in Switzerland. In this case, instead of using glued-in stainless steel cables, the electrodes were screws that were electrically insulated along the shank (Figure 16). In addition to the moisture content, also the environmental conditions, namely air temperature and relative humidity, were recorded. The recorded data was stored locally, but also uploaded to a server, from where it could be easily accessed.

Dietsch et al. (2015b) also installed similar systems in 21 large span timber structures in Germany. In this case, the electrodes were teflon-insulated probe pins used with common moisture content meters, introduced at various depths. Air temperature and relative humidity were also measured. Data had to be accessed locally, since no data transmission system was set up.

Franke et al. (2015) monitored four timber bridges in central Switzerland using the same commercial system as Tannert et al. (2011) and Dietsch et al. (2015b) to measure the moisture content. Air temperature and relative humidity were also monitored. The data could also be accessed remotely.

Koch et al. (2016; 2017) also used insulated stainless steel screws as electrodes, and the same commercial system used in the other studies, to monitor nine protected timber bridges in Germany.

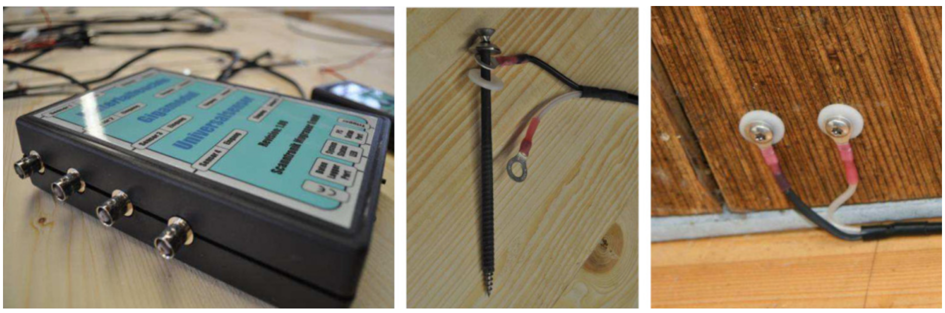


Figure 16. Moisture monitoring equipment (Tannert et al. 2011).

6.2 Timber bridges in the USA

The *Wood in Transportation* (WIT) program, initialy the *Timber Bridge Initiative*, was a national timber bridge program to encourage the use of wood as a structural material for highway bridges in the USA. Within the scope of this program, several rural timber bridges were built during the early 1990s. Many of these bridges were also regularly inspected and subjected to load tests. Seven of these bridges, namely hardwood timber bridges in Pennsylvania, were monitored over a four-year period (from 1997 to 2001), after being in service for approximately five years (Wacker et al. 2004). The load level in the pre-stressing bars (in stress-laminated decks) was monitored using load cells and moisture content was measured using common insulated probe pins, inserted at several locations and depths. In addition, air temperature and relative humidity in the vicinity of the bridges were also monitored, as well as the temperature inside the deck, to correct the moisture readings. The data was stored in a local data-logger (Figure 17).

Figure 17. Data-logger box and load test (Wacker et al. 2004).

6.3 Timber bridges in Norway

Beginning in 2000, five timber bridges in Norway were instrumented with moisture sensors, air temperature and relative humidity sensors and, in some of the bridges, also load cells to measure the the forces in the pre-stressing bars of the laminated decks (Aasheim 2013; Dyken and Kepp 2010). Moisture content was monitored using the hygrometric method (Section 5.1), which consists in measuring the temperature and relative humidity of an air pocket in equilibrium with the surrounding wood (Figure 18). Measurements were not only made inside the deck, but also in dummy wooden blocks attached to it. The adoption of this monitoring method could be due to the fact that the deck was pressure treated with creosote, which could significantly influence electrical resistance measurements made with electrodes. Nevertheless, unreasonable results were initially obtained using the hygrometric method and it had to be recalibrated, i.e. new correlations between air temperature, relative humidity and moisture content had to be established in laboratory tests (Dyken and Kepp 2010). This monitoring system operated for nine years. It was calibrated twice during this period and no significant changes in measurement accuracy were found, which shows the long-term stability of this moisture content measurement technique.

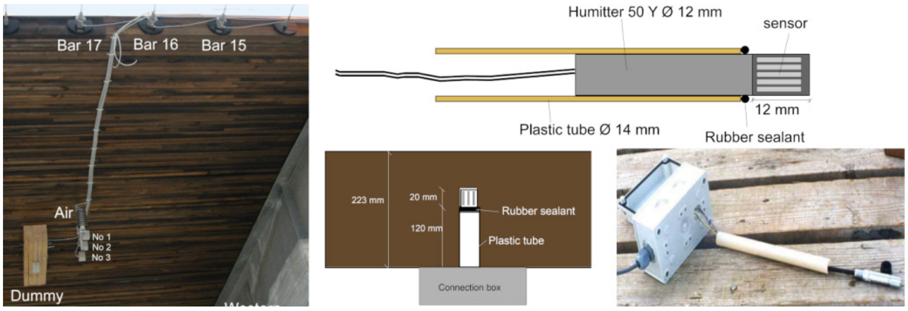


Figure 18. Monitoring instrumentation in a timber bridge (Aasheim 2013).

6.4 Timber structures in Sweden

6.4.1 Multi-storey timber buildings

The Limnologen complex, in Växjö, Sweden, comprises four eight-storey residential timber buildings. The structure is composed by cross-laminated timber (CLT) floors, CLT and timber-framed walls, and continuous steel rods that anchor the building to the concrete ground floor. In some parts of the buildings, glulam columns and beams are also used.

The monitoring system includes monitoring of vertical deformations, storey by storey, using resistive displacement sensors (Serrano 2009). These sensors are relatively easy to use, requiring almost no additional electronic instrumentation. The sensors were attached to a small bracket fixed at the top of the wall and to a bar that was, on the other end, fixed to the top of the wall of the floor below (Figure 19) . The air temperature and relative humidity next to the displacement sensors was also monitored.

Figure 19. Monitoring of vertical deformations (Serrano 2009).

6.4.2 Timber bridges

Björngrim et al. (2017) developed a moisture content sensor, based on measuring the electrical resistance of wood, that is composed by three thin electrodes. The first electrode is uninsulated and inserted up to a depth of 50 mm from the surface, the second electrode is also uninsulated and installed up to a depth of 100 mm, and the third electrode is insulated (except for the tip) and also installed up to a depth of 100 mm. Therefore, the moisture content in the outer 50 mm is obtained by measuring the electrical resistance between the first and second electrodes and the moisture content at a depth of 100 mm is obtained by measuring the electrical resistance between the second and third electrodes.

These sensors were installed in two road-traffic bridges (Figure 20). In one case the electrodes were installed after the bridge was erected and in the other they were installed during the production of the glulam elements.

Figure 20. Monitored road-traffic bridges, with signalled measurement locations (Björngrim et al. 2017).

A timber pedestrian bridge (Figure 21), also in Sweden, was been equipped with various wireless sensors for long-term monitoring (Björngrim 2015; Saraçoğlu et al. 2013). The sensors include accelerometers (blue dots in Figure 21), GNSS receivers to measure displacements (red dots in Figure 21), moisture content sensors (based on the electrical resistance method, yellow dots in Figure 21), strains sensors in the steel cables (black dots in Figure 21), and a weather station (green dot in Figure 21). The data loggers are located in a cabinet with controlled temperature in one of the abutments. The use of wireless sensors working at the same frequency is reported to have causes severe communication problems and data loss. Even wireless sensors in an adjacent building are said to cause communication problems between the sensors in the bridge and had to be turned off when the bridge sensors were measuring and communicating with the data logger. This shows another issue with wireless sensors, in addition to the need to access them to change batteries, and the limited data-transmission capabilities.

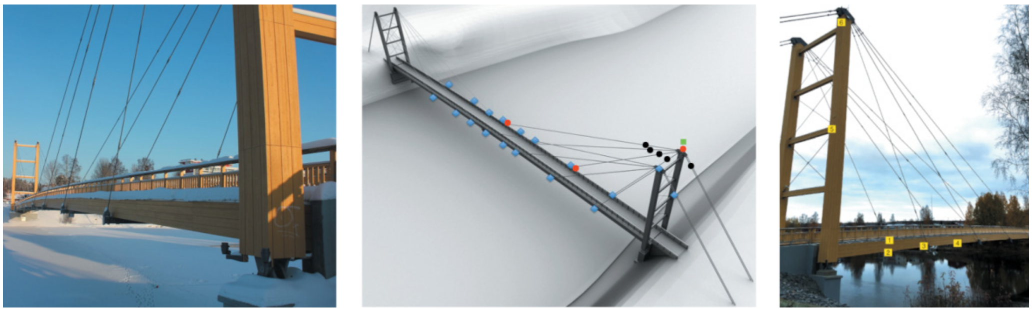


Figure 21. Monitored pedestrian bridge, with signalled measurement locations (Björngrim 2015).

6.5 Office building in Switzerland

An innovative post-tensioned hardwood timber-frame office building, named House of Natural Resources (HoNR), was erected in the campus of ETH Zurich, in Switzerland. The building was extensively instrumented (Leyder et al. 2017) and subjected to vibration-based tests during construction and after completion (Leyder 2018). The measured parameters include air temperature and relative humidity, moisture content, tendon forces, deformations, strains, and modal parameters. Moisture content was monitored using common insulated probe pins inserted at several locations and various depths (electrical resistance method). Tendon forces were measured using load cells mounted at the anchorage of each tendon. Deformations were measured using traditional topographic surveying methods, namely a robotic total station, during construction. Strains were measured using FBG sensors attached to the surface of some columns and beams. These sensors were 400 mm long and, therefore, provide average strains over this length. In addition to the FBG sensors, two distributed optical fibre sensors were also installed, which allow making strain measurements every 20 mm. Due to space constraints, these sensors had to be installed with a slight curvature and this is reported to have led to significant discontinuities in the data (Leyder 2018). These measurements were only conducted during a short period due the cost of the equipement.

7. Survey

A questionnaire related to monitoring of timber structures was sent to 22 engineering offices in Switzerland. The open-ended questions allowed the respondents to freely define main issues according to their experience and to better frame their answers. However, they also make the survey more difficult to summarise and report. A more extensive list of answers in presented in Section 7.3 and a summary and conclusions are presented in Section 7.4.

7.1 Questions

The questionnaire contained the questions presented below.

1. **Importance of structural/component monitoring**
   - 1.1 Have you considered specifying or specified the implementation of monitoring systems or plans?
   - 1.2 What types of monitoring systems or plans were considered (e.g. periodic visual inspections, periodic tachymetric surveys of displacements, continuous monitoring of ambient conditions and/or moisture content)?
   - 1.3 What locations and parameters were/would be monitored (e.g. connections, supports, load application areas, areas susceptible specific hazards)?
   - 1.4 What was the stage of the project when monitoring was considered (e.g. conception, design, construction, use)?
   - 1.5 What were the motives to consider monitoring (e.g. uncertainties regarding design assumptions, issues during construction, issues during use, damages)?
   - 1.6 Why was monitoring not implemented (e.g. not suitable for the specific situation, high costs, difficult to set up, large number of sensors needed, lack of time, lack of interest from other stakeholders)?
2. **Hotspots in timber structures**
   - 2.1 What are, in general, the most important parameters/properties to be monitored (e.g. displacements, moisture content)?
   - 2.2 For how long should they be monitored (e.g. for less than 1 week, 1 month to 1 year, several year?
   - 2.3 At what stage should the monitoring take place (e.g. during construction, immediately after construction, during use)?
   - 2.4 What should be required from the monitoring system (e.g. long-lasting batteries, wireless data transmission, easily setup, reusability)?
3. **Monitoring methods and technology**
   - 3.1 What are the most promising monitoring technologies that you are aware of (e.g. displacement measurement based on digital image analyses, adapters for wireless data transmission)?
   - 3.2 How did you become aware of them (e.g. trade show, own research, saw it implemented)?
   - 3.3 Would you consider using them? Why/why not?

3.4 What locations would you monitor (e.g. connections, supports, load application areas, areas susceptible specific hazards)?

Note: This question differs from question 1.3 in that the places to be monitored must be indicated here based on the available technologies known to you, while question 1.3 concerns the naming of hotspots in timber structures in general.

7.2 Respondents

The questionnaire was answered by 17 engineers from the following 15 companies (listed in alphabetical order):

- Borlini & Zanini SA, 6915 Pambio Noranco
- Fuhrmann Ingenieurbüro für Holzbau, 3800 Unterseen
- Holzing Maeder GmbH. 2533 Evilard
- Holzprojekt GmbH, 6003 Luzern
- Ingenieurbüro Silvio Pizio GmbH, 9427 Wolfhalden
- Josef Kolb AG, 8590 Romanshorn
- Krattiger Holzbau AG, 8580 Amriswil
- Lauber Ingenieure AG, 6003 Luzern
- Makiol Wiederkehr AG, 5712 Beinwil am See
- Merz Kley Partner AG, 9423 Altenrhein
- Pirmin Jung Ingenieure AG. 6026 Rain
- Renggli AG, 6210 Sursee
- Schilliger Holz AG, 6403 Küssnacht
- SJB Kempter Fitze AG, 8733 Eschenbach
- Timbatec Holzbauingenieure Schweiz AG, 3600 Thun

7.3 Answers

For each question, the topics mentioned in the various answers are listed underneath each question. Some answers addressed various topics and, therefore, the sum of the number of times that each topic was mentioned can be higher than the number of respondents.

1. **Importance of structural/component monitoring**

1.1 Implementation of monitoring systems or plans

- Only one company did not apply monitoring in practice yet.

1.2 Types of monitoring systems or plans considered

- periodic visual inspections of critical points
- control plans defined by the designer and conducted with the contractor after each important construction stage

1.3 Locations and parameters to be monitored

See answers to question 2.1

1.4 Stage of the project when monitoring was considered

- During use (generally motivated by an incident) .... ×9
- Depends strongly on the object .... ×4
- Execution planning stage .... ×3
- Execution stage .... ×3
- Concept or initial design stage .... ×2
- Detailed design stage .... ×2
- After rehabilitation .... ×1

1.5 Motives why monitoring was considered

- Incidents during use .... ×6
- Design uncertainties (moisture content of wood, shrinkage coefficient of concrete, stiffness of connections) .... ×5
- Incidents/uncertainties during construction .... ×4
- Damages detected (cracks, rot, corrosion, etc.) .... ×2
- To guarantee operability of the building (including fulfilling legal responsibilities of the owners) .... ×2
- Changes in use .... ×1
- Inspections required by the owner: .... ×1

1.6 Motives why monitoring was not implemented

- Owner not interested/will not pay for monitoring............................ ×14
- Too expensive or low cost/benefit ratio .... ×12
- Lack of knowledge about existing techniques................................... ×4
- Problem only recognized after visible damage occurred.............. ×4
- Not necessary .... ×5
- Not mandatory... ×2
- Low importance of the building.. ×1
- Specific monitoring system not available/not known .... ×1

2. Hotspots in timber structures

2.1 Important parameters/properties and locations to be monitored

- Moisture content
  - exposed zones
  - hidden cavities (e.g. in flat roof construction, at the base of outer walls, joints, plumbing voids)
  - block-glued elements and in big timber cross-sections (glulam, or CLT), due to moisture-induced stresses
  - areas where plant/flower boxes have been placed
  - lateral edges of roof coverings and membranes
  - waterproofing sealants
- Indoor and outdoor climate
- Deformations and displacements
  - settlement of foundations and structures
  - monitoring with tachymeters
  - to help verify modelling assumptions (e.g. in timber concrete composite structures)
  - connected to an alert system (e.g. via SMS, or email)
- Cracks and delaminations
  - areas subject to heavy stresses or essential for structural safety
- Pre-stressing forces
- Dynamic behaviour of floor, bridges and observation towers (for vibration mitigation)
- Loads (namely snow loads on roofs)
- Corrosion of metal fasteners
- Acoustic insulation (walls and slabs)
- Parts of a structure that are relevant for its integrity and prone to suffer damage
- Highly loaded members and connections

- Connections
  - in general and connections with big dimensions and/or involving different materials
  - in historical bridges, observation towers, etc.
  - expansion joints
  - bridge supports
- Bridges
  - supports
  - piers in the water level area
- Parts of structures with challenging/special geometries
- Zones without clearly defined stress states (punching, complex load paths, etc.)
- Contact zones between timber and massive sub-structure
- Fixation of external cladding

2.2 Duration of monitoring

- During entire service life ×10
- Several years ×7
- Depends on the structure ×4
- For 1 month to 1 year (should allow identifying maximum temperature and relative humidity) ×3
- Less than 1 week ×1

2.3 Stages during which monitoring should take place

- During entire service life ×11
- During construction and use ×5
- Depends on the structure and monitored parameter ×5
- During construction ×4
- Immediately after construction ×1

2.4 Important features of monitoring systems

- Wireless data transmission ×15
- Easy to set up and use ×12
- Easy to analyse and interpret data ×6
- Low cost ×6
- Off-grid power ×5
- Long-term operability (sensors, batteries, software, etc.) ×4
- Reusability of sensors ×4
- Collection of data in data bases ×3
- Simple maintenance ×3
- Alerts (via SMS, or email) ×3
- Integration in BIM software for building management ×3
- Data compression ×2

- Not compromise aesthetics of building/structure ×2

3. Monitoring methods and technology

3.1 Most promising monitoring methods and technologies

- Deformation measurements using optic methods (digital image analysis, 3D scanners, etc.) ×15
- Continuous moisture content measurements ×12
- Wireless sensors ×3
- Thermal imaging (to assess airtightness and moisture accumulation) ×2
- Acoustic emissions ×1
- Vibration-based methods that use ambient excitation ×1

3.2 Sources of knowledge

- Own literature reviews ×8
- Examples of practical applications ×7
- Information from colleagues ×5
- Technical publications ×5
- Continuing education events ×4
- Contact with producers and suppliers ×3
- Research and materials testing institutes and universities ×3
- Trade fairs ×2

3.4 Most important locations and parameters/properties to be monitored

See answers to question 2.1

An additional important application of non-destructive testing that also mentioned by some respondents is the non-destructive determination of the strength classes of timber elements in situ.

7.4 Conclusions

The main conclusions that can be drawn from the answers are listed below.

- Only one company had not applied monitoring yet.
- Monitoring is essential for special and/or important structures.
- Instead of relying on monitoring, the goal should be to create less vulnerable (i.e. more robust) and durable constructions that do not require monitoring.
- The implemented monitoring systems and strategies greatly depend on what is being monitored. Inspection intervals are planned in accordance with SIA 469, i.e. and main

inspections carried out by an expert every five years or after incidents and interim annual inspections by the owner, usually visual inspections.

- Damage avoidance:
  - monitoring may prevent small or localised damages from spreading and limit potential consequences;
  - monitoring may also help in taking urgent safety measures in due time (e.g. removing snow from roofs).
- The most important parameters to be monitored are:
  - moisture content of wood (continued monitoring)
  - deformations (including creep deformations) (continued or periodic monitoring)
  - indoor and outdoor climate (continued monitoring)
  - pre-stressing forces (continued or periodic monitoring)
- If there are changes in use or occupancy of a building:
  - monitoring is a good instrument for early damage detection if compromises had to be made in construction/design;
  - monitoring of deformations, loads, and ambient climate should be considered.
- Regarding costs:
  - it is often not clear if the client is willing to pay the costs related to monitoring
  - the designer should include monitoring activities and costs in the quotation
- Relationship between the designer, the owner, and the contractor:
  - proposing a monitoring system will raise questions about the quality of the design
  - monitoring shall not be mandatory, but a choice of the owner and the designer, depending on the structure/building and expected actions/exposures
  - even with well-intentioned owners, only limited financial resources are usually available for monitoring. Therefore, a project-specific overall concept with efficient measures should always be aimed at.

8. Conclusions

A broad variety of NDT methods has been developed and applied to wood and structural timber. However, not all NDT methods can be efficiently used for monitoring purposes and even fewer can be integrated in automated SHM systems. To be used in a SHM system, a NDT method must not only be able to continuously and reliably assess a specified property or parameter, but also comply with various operational requirements. This gap between research on NDT and practical applications can explain, in part, the reduced number of reported long-term monitoring studies of timber structures.

In last 10 years, some long-term SHM studies have been conducted. Most of them are focused on monitoring the moisture content of wood and the indoor/outdoor climate, due to its relevance to the behaviour and durability of timber and the low cost and simplicity of the necessary equipment. This has proven to be a reliable and effective strategy that is able to detect damage at an early stage, if the location of the sensors is adequately chosen.

Acoustic methods can be divided in ultrasonic and acoustic emission methods. Ultrasonic methods are widely and successfully used in non-destructive assessment of timber, namely to detect cracks and delaminations on structural members. The main disadvantages are the influence of the surface preparation and the difficulty of interpreting the results, namely in irregular and non-homogeneous elements. Acoustic emission methods are able to detect damage at a very early stage. Their main disadvantage is the practical difficulty of implementation in structural-sized elements, due to the required instrumentation and difficulty in discerning the acoustic emission signals from the background noise.

Vibration-based methods are one of the few NDT methods that could be able to monitor global changes in the structure, even using only ambient excitations. Their main disadvantage is that the lower frequencies that are typically measured are less sensitive to damage and might not be enough to locate it, unless a high number of sensors is used.

Optic methods allow a contact-free determination of displacements, surface deformations, and even vibrations. The use of optic methods in the automated monitoring of deformations and displacements is undergoing quick developments, namely through the use of photogrammetric methods based on image-analysis techniques. These methods do not require direct access to the structure, can provide large amounts of information, and can be set up with lower-cost components. However, they usually still exhibit lower accuracies than traditional surveying methods. Progress in this field is under heavy development, both regarding hardware and image-processing algorithms, and improved accuracies at lower costs should be possible.

The use of fibre-optic sensors is also a promising field, namely for monitoring strains in timber structural elements. The advantages of using fibre-optics sensors are the possibility of adapting them to measure various parameters, the possibility of having multiple sensors in a single optic fibre, their resistance to harsher environments, and their ability to also be used for high-frequency measurements. The disadvantages are the high cost of producing the sensors and of the data acquisition instrumentation, and the general lack of experience on how to properly install these sensors in timber elements

The main results of the survey on the monitoring of timber structures show that monitoring is already widely used, namely for important or special structures and that monitoring strategies are mostly decided on a case-by-case basis. It is recognised that monitoring may assist in preventing damage and the most important parameters to be monitored are the moisture content of wood, the indoor and outdoor climate, deformations and displacements, cracks and delaminations, and pre-stressing forces. It is usually not clear who should bear the costs of monitoring (the owner of the building, the designer, or the main contractor). It was also mentioned that proposing a monitoring system might raise questions about the quality of the design. The most important features of monitoring systems were wireless data transmission, ease of use (installation, operation, and interpretation of the results) and low cost. This is in agreement with the most recent SHM case studies and supports the need to bridge the gap between research on NDTs and their use in practice.

References

Aasheim, E. (2013). "Norwegian Timber Bridges: Current Trends and Future Directions." Conference presentation, Las Vegas, USA.

Agarwal, A., and Lang, J. (2005). *Foundations of Analog and Digital Electronic Circuits*. Morgan Kaufmann, Amsterdam; Boston.

Aicher, S., Höfflin, L., and Dill-Langer, G. (2001). "Damage evolution and acoustic emission of wood at tension perpendicular to fiber." *Holz als Roh- und Werkstoff*, 59(1–2), 104–116.

Aktan, A., Catbas, F., Grimmelsman, K., and Pervizpour, M. (2003). *Development of a model health monitoring guide for major bridges*. Intelligent Infrastructure and Transportation Safety Institute, Drexel University, 163.

Ansari, F. (2005). "Fiber optic health monitoring of civil structures using long gage and acoustic sensors." *Smart Materials and Structures*, 14(3), S1.

Ansell, M. P. (1982). "Acoustic emission from softwoods in tension." *Wood Science and Technology*, 16(1), 35–57.

ASTM E1316 - 00. *Standard Terminology for Nondestructive Examinations*. (2000). ASTM International, 38.

Baensch, F. (2015). "Damage evolution in wood and layered wood composites monitored in situ by acoustic emission, digital image correlation and synchrotron based tomographic microscopy." Doctoral Thesis, ETH Zurich.

Baker, M. C. (1969). "Decay of Wood." *Canadian Building Digest*, (CBD-112), 5 p.

Balageas, D., Fritzen, C.-P., and Güemes, A. (Eds.). (2006). *Structural Health Monitoring*. ISTE, London, UK.

Berkovic, G., and Shafir, E. (2012). "Optical methods for distance and displacement measurements." *Advances in Optics and Photonics*, 4(4), 441–471.

Björngrim, N. (2015). "Monitoring of a timber footbridge." Licentiate thesis, Luleå University of Technology, Luleå.

Björngrim, N., Fjellström, P.-A., and Hagman, O. (2017). "Robust, passive resistance sensor for moisture content monitoring of timber bridges." *Conference proceedings, ICTB 2017, 3rd International Conference on Timber Bridges*, RISE Research Institutes of Sweden, Skellefteå, Sweden, 10.

Blaß, H.-J., and Frese, M. (2010). *Schadensanalyse von Hallentragwerken aus Holz (Analyses of damages in timber hall structures)*. Karlsruher Berichte zum Ingenieurholzbau, Karlsruher Institut für Technologie (KIT), Karlsruhe, 124.

Brischke, C., and Rapp, A. O. (2010a). "Service life prediction of wooden components – Part 1: Determination of dose-response functions for above ground decay." *Proceedings of the 41st Annual Meeting of the International Research Group on Wood Protection (IRG41)*, International Research Group on Wood Protection (IRG), Biarritz, France, 14.

Brischke, C., and Rapp, A. O. (2010b). "Service life prediction of wooden components – Part 2: Impact of material, exposure and design details." *Proceedings of the 41st Annual Meeting of the International Research Group on Wood Protection (IRG41)*, International Research Group on Wood Protection (IRG), Biarritz, France, 17.

Brischke, C., Rapp, A. O., and Bayerbach, R. (2008a). “Measurement system for long-term recording of wood moisture content with internal conductively glued electrodes.” *Building and Environment*, 43(10), 1566–1574.

Brischke, C., Rapp, A. O., Bayerbach, R., Morsing, N., Fynholm, P., and Welzbacher, C. R. (2008b). “Monitoring the ‘material climate’ of wood to predict the potential for decay: Results from in situ measurements on buildings.” *Building and Environment*, 43(10), 1575–1582.

Brownjohn, J. M. W. (2007). “Structural health monitoring of civil infrastructure.” *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 365(1851), 589–622.

Bucur, V. (2003). *Nondestructive Characterization and Imaging of Wood*. Springer Series in Wood Science, Springer.

Bucur, V. (2006). *Acoustics of Wood*. Springer Series in Wood Science, Springer-Verlag, Berlin Heidelberg.

Bucur, V. (Ed.). (2011). *Delamination in Wood, Wood Products and Wood-Based Composites*.

Bucur, V., and Kazemi-Najafi, S. (2011). “Delamination Detection in Wood – Based Composites Panel Products Using Ultrasonic Techniques.” *Delamination in Wood, Wood Products and Wood-Based Composites*, Springer Netherlands, 307–351.

Büyüköztürk, O., Tasdemir, M. A., Güneş, O., and Akkaya, Y. (Eds.). (2013). *Nondestructive Testing of Materials and Structures*. RILEM Bookseries, Springer, Netherlands.

Charalampous, E., Psimoulis, P., Guillaume, S., Spiridonakos, M., Klis, R., Bürki, B., Rothacher, M., Chatzi, E., Luchsinger, R., and Feltrin, G. (2015). “Measuring sub-mm structural displacements using QDaedalus: a digital clip-on measuring system developed for total stations.” *Applied Geomatics*, 7(2), 91–101.

Choi, F. C., Li, J., Samali, B., and Crews, K. (2007). “Application of modal-based damage-detection method to locate and evaluate damage in timber beams.” *Journal of Wood Science*, 53(5), 394–400.

Daum, W. (2013). “Guidelines for Structural Health Monitoring.” *Handbook of Technical Diagnostics*, H. Czichos, ed., Springer Berlin Heidelberg, 539–541.

Deza, U. (2011). “Development, evaluation and implementation of sensor techniques for bridges critical to the national transportation system.” Doctoral Thesis, Iowa State University, Ames, Iowa.

DGZfP-B 9. *Merkblatt über die automatisierte Dauerüberwachung im Ingenieurbau* (2000). DGZtP-Richtlinie, Deutsche Gesellschaft für Zerstörungsfreie Prüfung e. V. (DGZfP), 22.

Diakhate, M., Bastidas-Arteaga, E., Moutou Pitti, R., and Schoefs, F. (2017). “Cluster analysis of acoustic emission activity within wood material: Towards a real-time monitoring of crack tip propagation.” *Engineering Fracture Mechanics*, 180, 254–267.

Dietsch, P., Franke, S., Franke, B., Gamper, A., and Winter, S. (2015a). “Methods to determine wood moisture content and their applicability in monitoring concepts.” *Journal of Civil Structural Health Monitoring*, 5(2), 115–127.

Dietsch, P., Gamper, A., Merk, M., and Winter, S. (2015b). “Monitoring building climate and timber moisture gradient in large-span timber structures.” *Journal of Civil Structural Health Monitoring*, 5(2), 153–165.

Dill-Langer, G., W.Bernauer, and Aicher, S. (2005). "Inspection of glue-lines of glued-laminated timber by means of ultrasonic testing." *Proceedings of the 14th International Symposium on Nondestructive Testing of Wood*, Shaker Verlag, University of Applied Sciences in Eberswalde, Germany.

Dinwoodie, J. M. (2000). *Timber: Its nature and behaviour*. Taylor & Francis.

Divos, F. (2011). "Delamination Evaluation of in-Service Glulam Beams and other Structural Members Via Ultrasonics." *Delamination in Wood, Wood Products and Wood-Based Composites*, Springer Netherlands, 353–364.

Dubois, F., Méité, M., Pop, O., and Absi, J. (2012). "Characterization of timber fracture using the Digital Image Correlation technique and Finite Element Method." *Engineering Fracture Mechanics*, 96, 107–121.

Dyken, T., and Kepp, H. (2010). "Monitoring the moisture content of timber bridges." *Proceedings of the International Conference on Timber Bridges (ITCB 2010)*, ICTB 2010 & Tapir Academic Press, Lillehammer, Norway, 223–235.

Ehrhart, M., and Lienhart, W. (2015). "Monitoring of civil engineering structures using a state-of-the-art image assisted total station." *Journal of Applied Geodesy*, 9(3), 174–182.

EN 1990:2002. *Eurocode – Basis of structural design*. (2002). European Committee for Standardization (CEN), Brussels, 87.

Farr, I., and Chesmore, D. (2007). "Automated bioacoustic detection and identification of wood-boring insects for quarantine screening and insect ecology." *Proceedings of theProceedings of the 4th International Conference on Bioacoustics*, 3, 201–208.

Farrar, C. R., Doebling, S. W., and Nix, D. A. (2001). "Vibration–based structural damage identification." *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 359(1778), 131–149.

Farrar, C. R., and Worden, K. (2007). "An introduction to structural health monitoring." *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 365(1851), 303–315.

Forsén, H., and Tarvainen, V. (2000). *Accuracy and functionality of hand held wood moisture content meters*. VTT Publications, VTT, Espoo, 79.

Fraden, J. (2010). *Handbook of Modern Sensors: Physics, designs, and applications*. Springer-Verlag, New York.

Franke, B., Franke, S., and Müller, A. (2015). "Case studies: long-term monitoring of timber bridges." *Journal of Civil Structural Health Monitoring*, 5(2), 195–202.

Früwald, E., Serrano, E., Toratti, T., Emilsson, A., and Thelandersson, S. (2007). *Design of safe timber structures - How can we learn from structural failures in concrete, steel and timber?* Lund Institute of Technology, Lund University, Lund, 222.

Gautschi, G. (2002). *Piezoelectric Sensorics: Force Strain Pressure Acceleration and Acoustic Emission Sensors Materials and Amplifiers*. Springer-Verlag, Berlin Heidelberg.

Glass, S. V., and Zelinka, S. L. (2010). "Moisture relations and physical properties of wood." *Wood handbook: wood as an engineering material*, Forest Products Laboratory, Madison, USA, 5-1-5–46.

Habel, W., Schukar, V., and Hofmann, D. (2014). "Requirements to establish fibre-optic sensors for monitoring of structures." *Proceedings of the 7th European Workshop on Structural Health Monitoring (EWSHM 2014)*, Nantes, Franc, 2330–2337.

Hale, J. M., and Chapman, M. M. (2014). "Design, Installation and Calibration of a Strain Gauge Structural Monitoring System for a Timber Windmill." *Experimental Techniques*, 38(3), 45–53.

Hamann, M., Kubowitz, P., and Hofmann, D. (2013). "Scale of intelligence in hybrid bridge structures – New aspects of monitoring by using fibre-optic sensors in timber elements." *Proceedings of the 6th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-6 2013)*, Hong Kong.

Henke, K., Pawlowski, R., Schregle, P., and Winter, S. (2015). "Use of digital image processing in the monitoring of deformations in building structures." *Journal of Civil Structural Health Monitoring*, 5(2), 141–152.

Hoult, N. A., Andy Take, W., Lee, C., and Dutton, M. (2013). "Experimental accuracy of two dimensional strain measurements using Digital Image Correlation." *Engineering Structures*, 46, 718–726.

Huston, D. (2010). *Structural Sensing, Health Monitoring, and Performance Evaluation | Taylor & Francis Group*. CRC Press, Boca Raton.

Ibach, R. E. (2012). "Biological Properties of Wood." *Handbook of Wood Chemistry and Wood Composites*, CRC Press, 99–126.

James, W. (1988). *Electric moisture meters for wood*. General Technical Report, Forest Products Laboratory, 17.

Jiang, R., Jáuregui, D. V., and White, K. R. (2008). "Close-range photogrammetry applications in bridge measurement: Literature review." *Measurement*, 41(8), 823–834.

Jockwer, R. (2014). "Structural behaviour of glued laminated timber beams with unreinforced and reinforced notches." Doctoral Thesis, ETH Zurich.

K. Bremer, M. Wollweber, F. Weigand, M. Rahlves, M. Kuhne, R. Helbig, and B. Roth. (2016). "Fibre Optic Sensors for the Structural Health Monitoring of Building Structures." *Procedia Technology*, Elsevier, Paderborn, 524–529.

Karbhari, V. M., and Ansari, F. (Eds.). (2009). *Structural Health Monitoring of Civil Infrastructure Systems*. Woodhead Publishing Series in Civil and Structural Engineering, Woodhead Publishing.

Kasal, B., Lear, G., and Tannert, T. (2010). "Stress waves." *In Situ Assessment of Structural Timber*, RILEM State of the Art Reports, B. Kasal and T. Tannert, eds., Springer, Netherlands, 5–24.

Kasal, B., and Tannert, T. (Eds.). (2010). *In Situ Assessment of Structural Timber*. RILEM State of the Art Reports, Springer, Netherlands.

Kawamoto, S., and Williams, R. S. (2002). *Acoustic emission and acousto-ultrasonic techniques for wood and wood-based composites: a review*. General Technical Report (GTR), Forest Products Laboratory, Madison, USA, 16.

Koch, J., Arndt, R., Simon, A., and Jahreis, M. (2017). "Moisture monitoring of nine protected timber bridges in Germany." *Conference proceedings, ICTB 2017, 3rd International Conference on Timber Bridges*, RISE Research Institutes of Sweden, Skellefteå, Sweden, 10.

Koch, J., Gräfe, M., and Arndt, R. W. (2016). "Monitoring of moisture content of protected timber bridges." *Proceedings of the 2016 World Conference on Timber Engineering (WCTE 2016)*, 8.

Kurz, J. H., and Boller, C. (2015). "Some background of monitoring and NDT also useful for timber structures." *Journal of Civil Structural Health Monitoring*, 5(2), 99–106.

Lamy, F., Takarli, M., Angellier, N., Dubois, F., and Pop, O. (2015). "Acoustic emission technique for fracture analysis in wood materials." *International Journal of Fracture*, 192(1), 57–70.

Law, D. W., Silcock, D., and Holden, L. (2018). "Terrestrial laser scanner assessment of deteriorating concrete structures." *Structural Control and Health Monitoring*, 25(5), e2156.

Leyder, C. (2018). "Monitoring-based performance assessment of an innovative timber-hybrid building." PhD Thesis, ETH Zurich, Zurich, Switzerland.

Leyder, C., Wanninger, F., Chatzi, E., and Frangi, A. (2017). *Laboratory tests on a post-tensioned timber frame*. Report, ETH Zurich.

Lichti, D. D., and Jamtsho, S. (2006). "Angular resolution of terrestrial laser scanners." *The Photogrammetric Record*, 21(114), 141–160.

Lüchinger, P. (1996). "Basis of design: serviceability aspects." *IABSE reports = Rapports AIPC = IVBH Berichte*, 74, 33–40.

Maas, H.-G., and Hampel, U. (2006). "Photogrammetric Techniques in Civil Engineering Material Testing and Structure Monitoring." *Photogrammetric Engineering & Remote Sensing*, 72(1), 39-45(7).

Mankin, R. W., Hagstrum, D. W., Smith, M. T., Roda, A. L., and Kairo, M. T. K. (2011). "Perspective and Promise: a Century of Insect Acoustic Detection and Monitoring." *American Entomologist*, 57(1), 30–44.

Moore, J. C., Glenncross-Grant, R., Mahini, S. S., and Patterson, R. (2012). "Regional Timber Bridge Girder Reliability: Structural Health Monitoring and Reliability Strategies." *Advances in Structural Engineering*, 15(5), 793–806.

Moore, J., Glencross-Grant, R., Mahini, S., and R.Patterson. (2011). "Towards predictability of bridge health." *Sustaining Our Regions: The Engineering Challenge . Proceedings of 2011 Engineers Australia Regional Convention*, Australia, 103–110.

Mufti, A., Bakht, B., Humar, J., Jalali, J., Newhook, J., and Rahman, S. (2001). *Guidelines for structural health monitoring – Design Manual No. 2*. ISIS Canada, Intelligent Sensing for Innovative Structures, Winnipeg, Canada.

Mukupa, W., Roberts, G. W., Hancock, C. M., and Al-Manasir, K. (2017). "A review of the use of terrestrial laser scanning application for change detection and deformation monitoring of structures." *Survey Review*, 49(353), 99–116.

Murata, K., Masuda, M., and Ukyo, S. (2005). "Analysis of strain distribution of wood using digital image correlation method." *Transactions of the Visualization Society of Japan*, 25(9), 57–63.

Niemz, P., and Lühmann, A. (1992). "Anwendung der Schallemissionsanalyse zur Beurteilung des Bruchverhaltens von Holz und Holzwerkstoffen (Application of the acoustic emission analysis to evaluate the fracture behaviour of wood and derived timber products)." *Holz als Roh- und Werkstoff*, 50(5), 191–194.

Nor, N. M. (2018). "Structural health monitoring through acoustic emission." *Eco-Efficient Repair and Rehabilitation of Concrete Infrastructures*, Woodhead Publishing Series in Civil and Structural Engineering, Woodhead Publishing, 123–146.

Oliver-Villanueva, J. V., and Abián-Pérez, M. A. (2013). "Advanced wireless sensors for termite detection in wood constructions." *Wood Science and Technology*, 47(2), 269–280.

Olsen, M. J., Kuester, F., Chang, B. J., and Hutchinson, T. C. (2010). "Terrestrial laser scanning-based structural damage assessment." *Journal of Computing in Civil Engineering*, 24(3), 264–272.

Park, G., Rosing, T., Todd, M. D., Farrar, C. R., and Hodgkiss, W. (2008). "Energy Harvesting for Structural Health Monitoring Sensor Networks." *Journal of Infrastructure Systems*, 14(1), 64–79.

Park, H. S., Lee, H. M., Adeli, H., and Lee, I. (2007). "A new approach for health monitoring of structures: terrestrial laser scanning." *Computer-Aided Civil and Infrastructure Engineering*, 22(1), 19–30.

Pence, T. (2013). "Development of a smart timber bridge - sensor evaluation and data processing techniques." MSc Thesis, Iowa State University, Ames.

Perles, A., Mercado, R., Capella, J. V., and Serrano, J. J. (2016). "Ultra-Low Power Optical Sensor for Xylophagous Insect Detection in Wood." *Sensors (Basel, Switzerland)*, 16(11).

Phares, B. M., Wipf, T. J., and Deza, U. (2010). *Evaluation of Techniques for Embedding and Attaching FBG Sensors to New Glulam Bridge Members. 2010. Bridge Engineering Center; Iowa State University. Ames, IA*. Bridge Engineering Center; Iowa State University. Ames, Bridge Engineering Center, Iowa State University, Ames.

Pinkl, S., Herwijnen, H. W. G. van, Veigel, S., Gindl-Altmutter, W., and Riegler, M. (2018). "Urea-formaldehyde microspheres as a potential additive to wood adhesive." *Journal of Wood Science*, 1–8.

Porteous, J., and Kermani, A. (2009). "EC5 - Deformation and creep of timber structures." *The Structural Engineer*, 87(17), 8.

Porteous, J., and Kermani, A. (2013). *Structural Timber Design to Eurocode 5*. Wiley-Blackwell.

Reinprecht, L. (2016). *Wood Deterioration, Protection and Maintenance*. John Wiley & Sons, Ltd, Oxford, UK.

Rescalvo, F. J., Valverde-Palacios, I., Suarez, E., Roldán, A., and Gallego, A. (2018). "Monitoring of carbon fiber-reinforced old timber beams via strain and multiresonant acoustic emission sensors." *Sensors*, 18(4), 1224.

R.J. Ross, R.C. DeGroot, W.J. Nelson, and P.K. Lebow. (1997). "The relationship between stress wave transmission characteristics and the compressive strength of biologically degraded wood." *Forest Products Journal*, 47(5), 89–93.

Robbins, W. P., Mueller, R. K., Schaal, T., and Ebeling, T. (1991). "Characteristics of acoustic emission signals generated by termite activity in wood." *Proceedings of the IEEE 1991 Ultrasonics Symposium*, 1047–1051.

Ross, R. J. (Ed.). (2015). *Nondestructive Evaluation of Wood*. General Technical Report, Forest Products Laboratory.

Ross, R. J., and Pellerin, R. F. (1994). *Nondestructive testing for assessing wood members in structures: a review*. General Technical Report, Forest Products Laboratory, 40.

Rücker, W., Hille, F., and Rohrmann, R. (2006). *Guideline for Structural Health Monitoring*. SAMCO Final Report 2006, Federal Institute of Materials Research and Testing (BAM), Berlin, Germany, 63.

Rytter, A. (1993). "Vibrational Based Inspection of Civil Engineering Structures." PhD Thesis, University of Aalborg, Aalborg, Denmark.

Sanabria, S. (2012). "Air-coupled ultrasound propagation and novel non-destructive bonding quality assessment of timber composites." Doctoral Thesis, ETH Zurich.

Sandoz, J. L. (1989). "Grading of construction timeber by ultrasound." *Wood Science and Technology*, 23(1), 95–108.

Saraçoğlu, E., Gustafsson, A., and Fjellström, P. A. (2013). "Short-term monitoring of a cable-stayed timber footbridg." *Proceedings of the 2nd International Conference on Timber Bridges (ICTB 2013)*, Las Vegas, USA, 10.

Serrano, E. (2009). *Documentation of the Limnologen Project: Overview and summaries of sub projects results*. Växjö University, School of Technology and Design, 94.

Serrano, E., and Enquist, B. (2005). "Contact-free measurement and non-linear finite element analyses of strain distribution along wood adhesive bonds." *Holzforschung*, 59(6), 641–646.

Shan, J., and Toth, C. K. (2018). *Topographic laser ranging and scanning - principles and processing*. CRC Press, Boca Raton.

SIA 260:2013. *Basis of Structural Design*. (2013). SIA, Zurich, Switzerland, 44.

SIA 265:2012. *Holzbau*. (2012). SIA, Zurich, Switzerland, 100.

Sieffert, Y., Vieux-Champagne, F., Grange, S., Garnier, P., Duccini, J. C., and Daudeville, L. (2016). "Full-field measurement with a digital image correlation analysis of a shake table test on a timber-framed structure filled with stones and earth." *Engineering Structures*, 123, 451–472.

Sohn, H., Farrar, C. R., Hemez, F. M., Shunk, D. D., Stinemates, D. W., Nadler, B. R., and Czarnecki, J. J. (2004). *A review of structural health monitoring literature: 1996-2001*. Los Alamos National Laboratory Report, Los Alamos National Laboratory, 301.

Sutton, M. A., Orteu, J. J., and Schreier, H. (2009). *Image correlation for shape, motion and deformation measurements: basic concepts, theory and applications*. Springer, US.

Tannert, T., Berger, R., Vogel, M., and Müller, A. (2011). "Remote moisture monitoring of timber bridges: a case study." Cancún, México, 9.

Thelandersson, S., and Larsen, H. J. (Eds.). (2003). *Timber Engineering*. Wiley.

Valença, J., Júlio, E. N. B. S., and Araújo, H. J. (2011). "Applications of Photogrammetry to Structural Assessment." *Experimental Techniques*, 36(5), 71–81.

Vezočnik, R., Ambrožič, T., Sterle, O., Bilban, G., Pfeifer, N., and Stopar, B. (2009). "Use of terrestrial laser scanning technology for long term high precision deformation monitoring." *Sensors (Basel, Switzerland)*, 9(12), 9873–9895.

Wacker, J. P., Calil, C. J., Hislop, L. E., Hilbrich Lee, P. D., and Kainz, J. A.; (2004). *Long-term performance monitoring of hardwood timber bridges in Pennsylvania*. Research Paper, Forest Products Laboratory, Madison, USA, 56.

Wadley, H. N. G. (1986). "Acoustic Emission: Nature's Ultrasound." *Review of progress in quantitative nondestructive evaluatio*, Springer Science+ Business Media, LLC, Virginia, USA, 271–293.

Wagner, A., Wasmeier, P., Reith, C., and Wunderlich, T. (2013). "Bridge monitoring by means of video-tacheometer - A case study." *avn - Allgemeine Vermessungs-Nachrichten*, 120, 283–292.

Wagner, A., Wiedemann, W., Wasmeier, P., and Wunderlich, T. (2016). "Monitoring concepts using image assisted total stations." *SIG 2016: Proceedings of the International Symposium on Engineering Geodesy*, Croatian Geodetic Society, Varaždin, Croatia, 12.

Walser, B. H. (2004). "Development and calibration of an image assisted total station." Doctoral Thesis, ETH Zurich, Zurich, Switzerland.

Winandy, J. E. (2017). "Relating wood chemistry and strength: Part II. Fundamental relationships between changes in wood chemistry and strength of wood." *Wood and Fiber Science*, 49(1), 2–11.

Winandy, J. E., and Rowell, R. M. (2012). "Chemistry of wood strength." *Handbook of Wood Chemistry and Wood Composites*, CRC Press, 413–456.

Winkler, C., and Schwarz, U. (2014). "Multifunctional Wood-Adhesives for Structural Health Monitoring Purposes." *Materials and Joints in Timber Structures*, RILEM Bookseries, Springer, Dordrecht, 381–394.

Winkler, J., and Hendy, C. (2017). "Improved Structural Health Monitoring of London's Docklands Light Railway Bridges Using Digital Image Correlation." *Structural Engineering International*, 27(3), 435–440.

Worden, K., Farrar, C. R., Manson, G., and Park, G. (2007). "The fundamental axioms of structural health monitoring." *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 463(2082), 1639–1664.

Xu, Y.-L., and He, J. (2017). *Smart Civil Structures*. CRC Press, Boca Raton.

Zhou, X., Xia, Y., Wei, Z., and Wu, Q. (2012). "A videogrammetric technique for measuring the vibration displacement of stay cables." *Geo-spatial Information Science*, 15(2), 135–141.