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# ASSESSMENT AND MONITORING OF HISTORICAL TIMBER CONSTRUCTION: AVAILABLE TOOLS TO SUPPORT DECISION-MAKING PROCESSES.

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**Abstract.** *Timber structures represent a rich although still underestimated portion of the historical built asset worldwide documenting a tradition of sustainable practices and craftsmanship. Assessment of their condition is a fundamental step towards their conservation. While some overarching approaches for the assessment of timber structures are not dissimilar to those used for other types of structures, there are some specific factors affecting timber structures behavior that should be taken into consideration. Such factors are especially related to the organic nature of wood, which makes timber's properties largely variable and influenced by the environment. Successful conservation of historical timber structures requires combination of many different disciplinary contributions, from wood science and technology, to structural engineering, building physics, architecture, art history and environmental science, among others. This contribution aims to present an overview of tools supporting decision-making processes for the assessment and conservation of existing timber structures, including both methodological frameworks and technical approaches for data collection and analysis. These tools are reviewed according to the scope of the assessment and considering multiple levels at which timber structures are studied, at the material, system and building scale. Additionally, emerging approaches and challenges for holistic assessment of historical timber structures are discussed.*

## 1. INTRODUCTION

In the last decades, institutions, authorities and various stakeholders have recognized the urgent need to maintain and preserve a rich and diverse cultural asset, represented by traditional timber structures. Ad hoc international and national technical committees, such as ICOMOS's IWC (International Wood Committee) and ISCARSAH (International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage), RILEM TC 215 AST (in situ assessment of timber), RILEM TC RTE (Reinforcement of Timber Elements in Existing Structures), and the Working Group 10 of the CEN TC 346 " Conservation of cultural property", have been created to evaluate and develop decision-making tools for the assessment and conservation of (timber) structures of historical and cultural interest.

Information on traditional timber structures, acquired by means of structural health monitoring (SHM) and assessment methods, is fundamental to support decision-making processes. The discipline of structural health assessment and monitoring of timber structures is nowadays critical to the success of many conservation projects, and requires increasingly articulated and multidisciplinary skills. For these reasons, an interdisciplinary, multiscale approach (from the material to the building and context) is required for the assessment of timber structures.

This contribution aims to discuss the state-of-the-art by providing an overview of tools supporting decision-making processes for the assessment and conservation of existing timber structures. Methodological frameworks and technical approaches for data collection and analysis are reviewed according to the scope of the assessment and considering multiple levels at which timber structures are studied, at the material, system and building scale. Additionally, emerging approaches and challenges for holistic assessment of historical timber structures are discussed.

### 1.1. The decision-making process

Decision-making processes related to the management of heritage buildings is a challenging task due to conflicting priorities pursued by multiple stakeholders. As an example, intervention to complying with code requirements, such as those addressing seismic or energy performance, may conflict with the need of safeguarding the historical value and authenticity of a traditional timber system, without altering the original static scheme and, in some cases, maintaining the original features of a building enclosure. [1] describe, for instance, issues arisen with the seismic retrofitting of masonry buildings in Italy, as an application of building codes in force in the 1980s and 1990s, which caused the frequent replacement of existing timber floors and roofs with solid or hollow-core concrete diaphragms. Besides the loss of a vast historical built asset, these interventions proved to be ineffective and even detrimental, leading to failures during seismic episodes, due to increased loads, punching shear action of the new rigid slabs and overturning mechanism of the external walls [1].

Considering the complexity of choices associated with the assessment and conservation of historical timber structures, Multi-criteria Decision Analysis (MCDA) can support decision making processes, helping evaluation of a variety of conflicting and non-homogeneous criteria. A review on different approaches in the use of MCDA models for the preservation of historical built asset has been proposed in [2]. An example of application of a decision-making tool to assess energy efficiency and overall carbon footprint during maintenance and adaptive interventions of historical wooden façades is reported in [3].

The aim of the assessment is to facilitate the decision-making process, support a more sensible approach to the preservation and reduce the costs of the required interventions. As a matter of fact, the “cost of information” should offset the cost of intervention, and possibly have additional non-economic benefits. Diverse procedures and tools can assist experts in the assessment of timber structures. However, the value of historic buildings may justify greater expenses in sophisticated survey procedures and use of multiple methodologies for the diagnosis and assessment of timber structures.

Recent advances of sensing technologies have allowed for development of Structural Health Monitoring (SHM) systems, which provide information on the condition of a system and evaluate time-dependent phenomena which can affect a building performance. Monitoring systems may therefore serve for supporting decisions pertaining to the planning of appropriate inspection and maintenance actions in case of (or to avoid) damage or deterioration, as well to evaluate the effectiveness and long-term performance of an intervention.

Structural health monitoring of timber structures is generally categorized in two main areas: hygrothermal and structural monitoring, depending on the type of action, environmental or mechanical, respectively. The hygrothermal behaviour of wooden assemblies has significant influence on the durability and service life of timber buildings. Environmental factors are generally considered also in structural monitoring, as they have an impact on how reliably a timber structure can carry current or future loads. Therefore, multiple data are typically acquired in a SHM program. SHM strategies may be optimized considering the Value of Information (VoI) from the SHM systems [4]. Accordingly, the placement of sensing devices can limited to the minimal amount required for the control (and possibly correlation) of the identified key parameters affecting a timber structure performance, with the goal to holistically identify potential deterioration processes and even prevent damage to occur.

A literature review [5] found that on a total of 193 timber structures monitored from 1980 to 2019, 86 were existing buildings and 42 of them were historic timber structures, which were monitored to assess their safety and serviceability or to develop maintenance plans. The survey also found that, while in the past most SHM projects were aimed at the conservation of existing/historical timber structures (with a principal geographic concentration in Europe), more recently the focus has been shifting to new timber construction [5]. Some open questions are: what has been the use and value of information from previous SHM programs of historical timber structures? Can we increase the VoI from on-going and future SHM of historical timber structures?

### 1.2. Workflows: data production and interoperability

Assessment of historical timber structures encompasses different types and levels of analysis to consider technological, structural, material and architectonic features at the different scales of a structure, as well as inter-dependences between those features. Consequently, data should be collected in a way that allows various experts involved in the assessment to easily communicate and process information. [6] review available standards, guidelines and other practice-oriented documents supporting the assessment of historical timber structures. Reviewed documents are discussed in light of their use for specific assessment purposes, namely for a) the documentation of the building for conservation/preservation purposes, b) vulnerability and damage assessment, with a specific focus on seismic performance, and c) analytical assessment for serviceability and safety evaluation [6].

Categories of data which are collected in various stages, and for different assessment scopes, encompass: environmental data and wood moisture content (see section 2.1 of this paper); data for the mechanical characterization of the timber structural elements (section 2.2); data descriptive of alterations to the original structural systems and individual timber members (section 2.3) and geometrical data (section 2.4). As a result, different data types and formats are collected at multiple scales and by using various procedures, thus leading to issues of interoperability as well as of physical, spatial and statistical correlation.

The Swiss standard SIA 265/5:2011 [7], and the guidelines developed within the COST Action IE0601 [8] and further implemented in the prEN 1712 by the Working Group 10 of the CEN TC 346 [9], are to date the only available documents that consider the different levels of the investigations at the various hierarchical levels of a timber structure.

[8] describe stages and tasks for the assessment of historical timber structures, with a particular emphasis on technological aspects. The procedure consists in three different stages of analysis. The preliminary assessment entails historical survey, preliminary visual survey, measured survey (geometry, technology, damage), and preliminary structural analysis. A detailed survey of timbers aims to identify wooden species, estimate wood moisture content and mechanical parameters, and assess biological damage. A visual strength grading procedure adapted for grading timbers on site and originally developed in the Italian UNI 11119:2004 [10]is referred in [8]. The third stage of the assessment process is a technological survey of timber joints.

Visual inspection is a fundamental first step for all different scopes and levels of assessment. [6] and [11] present a digital template to collect information during visual inspection, by considering the different hierarchical levels of a timber structure: from the building as a whole, the structural complex and system/s, the timber elements and the connecting joints. Following this multi-scale approach, the template includes a section for damage assessment [11]. While the template is designed to be adapted to different construction types, its implementation and initial use have been limited so far only to timber roof systems typical of the Western construction tradition.

Other forms of assessment templates are available, and mainly target a specific scope of the assessment. These tools are generally meant to enable a standardized and rapid visual screening and data collection on site. Among them, it is worth mentioning the AeDES form to assess seismic damage [12], forms to assess causes of failures in engineered timber roof structures [13], [14], [15], and forms to assess the seismic vulnerability of traditional Italian timber roof structures [16]. It is worth mentioning that the latter is the only one, among the three cases above, specifically addressing historical timber systems.

Traditional paper forms have been increasingly replaced with digitally-supported tools to be used on mobile devices, thus expediting the inspection activities and enabling almost real-time data sharing. The use of digital platforms for data collection can be two-fold: to facilitate and standardize data collection, storage and sharing; and to allow for automatic or semi-automatic analysis in decision making processes.

Periodic inspection is one application where the first type of platform can be particularly useful. For instance, a bridge inspection procedure based on a software tool has been extensively used to inspect and monitor timber bridges in Slovenia [17][18].

The second approach requires structured data acquisition so that data can be exploited by automated reasoning systems. In the MONDIS Project [19] a knowledge-based system has been developed to support damage assessment of historical buildings. The main scope of the developed “Monument Damage Ontology” is to enable collaboration and data-sharing within the expert community, as well as to integrate existing data from different sources [19]. On line, expert-trained systems accessible from mobile devices have been developed to support time-sensitive, decision-making processes during assessment of damaged structures (for instance, planning shoring and repairs to avoid imminent collapse) (see for instance, [20]. The FaMIVE (Failure Mechanism Identification and Vulnerability Evaluation) [21], has been designed to be a flexible data collection platform for vulnerability assessment of historical structures, including traditional timber roofs and floors. More recently, this platform has been further developed to rapidly assess seismic and wind response of timber roofs [22]. It is worth noting, that most of the available documents for vulnerability/damage assessment refer to specific structural types or class of buildings. Therefore, many heritage timber structures, which do not fall in the covered categories, cannot be assessed with the codified criteria. The reader can find a more exhaustive review of inspection and assessment formats in [6].

Following visual inspection, further stages of the assessment pose additional challenges for data interoperability. While integration and spatial/physical correlation of non-destructive (NDT) and semi-destructive (SDT) testing data in a holistic assessment platform is becoming an increasing need, use of non-destructive (NDT) and semi-destructive (SDT) testing techniques for the assessment of timber structures is far from being a standardized procedure [23][24][25]. In sections 2.2 and 2.3, some studies focusing on data mining and multivariate analysis approaches of multi-sensor data to support decision making process are cited.

In the last two decades, multiple strategies have been developed for range- and image-based modelling techniques for buildings surveys. Seamless integration of 3D geometric data from 3D scanning or photogrammetry, building information modelling (BIM) and finite element modelling (FEM) is one of the emerging research topics in the field of cultural heritage management and structural health assessment and monitoring, which has seen some promising applications on heritage timber structures. In section 2.4, metric and non-metric data flow and interoperability among different tools supporting modelling tasks are discussed.

## 2. STATE OF THE ART AND EMERGING APPROACHES IN THE ASSESSMENT AND MONITORING OF HISTORICAL TIMBER STRUCTURES

In the following sections, different operational categories involved in the assessment of timber structures are introduced; state of the art tools and emerging approaches for the acquisition and analysis of data are then discussed for each category. Information acquired can be used for the assessment of both load-bearing and non-load-bearing timber elements, or applied just to the former category, when related to mechanical and structural performance.

### 2.1. Environmental and hygrothermal conditions

Type, magnitude, duration and frequency of environmental loads acting on a building should be evaluated in the structural assessment process, as they can greatly affect the performance of timber structures. As a hygroscopic material, wood exchanges moisture with the surrounding environment. Moisture content (MC) changes in the hygroscopic range (0-28%) affect wood physical and mechanical property. Therefore, MC measurement is important for correct strength grading (see section 2.2) and calibration of non-destructive (NDT) and semi-destructive (SDT) measurements [23]. Long-term, load-bearing behaviour of timber members (i.e., creep) can be negatively influenced by prolonged or recurrent exposure to a humid microclimate [26]. Additionally, MC changes in the hygroscopic range induce dimensional movement of the elements in service, with possible deformations, disconnections or occurrence of internal stresses due to constrained swelling or shrinkage [27].

In conditioned indoor climates, wood moisture content typically ranges between 8-12%. However, damage or defects of the building enclosure can expose wood to bulk liquid (e.g., a leak) or condensation, resulting in undesirable moisture gains which can reach the fiber saturation point (FSP, ~28%). This condition makes wood more susceptible to fungal attack that ultimately reduces the material structural integrity. Therefore, detection of moist areas is important as those areas are at risk of bio-deterioration.

Electrical and hygrothermal methods are the most common approaches to estimate and monitor MC in timber members. [23] and [28] review methodological criteria for MC estimation and monitoring using these non-destructive techniques. It is worth mentioning that large structural timbers are often characterised by non-uniform moisture distribution, which can vary along a member length and cross section. As moisture content estimates from resistance or capacitance data only depict local conditions, challenges in terms of data sampling are implicit with these methods, and require careful evaluation of potential vulnerable/more exposed areas, where moisture can reach higher values. These challenges are common to both historical and modern timber construction, and some sampling criteria to monitor wood moisture content in modern mass timber buildings are discussed in [29].

Long-term moisture content monitoring has proven to be effective to support decision-making processes in the conservation of historical timber structures [5]. Some authors highlight the importance of data processing of continuous moisture content data to support decision making processes related to the service life management of the monitored structure. Post-processing techniques such as moving average and erroneous data omission [29] have been proposed to improve data readability and automatize some analytical procedures.

Wave-based NDT imaging of wood has a great potential as preliminary non-contact screening procedure to detected moist areas along a timber member. Active thermography, for instance, can be used with some success to localize surface areas with high moisture content [30], [31]. Microwave reflectometry (MWR) can be used for detection of high moisture content in wood [32]. However, since MWR is affected by water, but also by decay and defects in wood, the simultaneous presence of many heterogeneities can be masked in MWR maps [32].

### 2.2. Mechanical characterization of timber members

Structural timber members present a high variability of properties (within and among members) which are affected by material and environmental factors, such as wood species, density, naturally occurring heterogeneities and moisture content. Some of these factors, such as the presence of knots, have a different impact on the mechanical behaviour of a timber member, depending on a member's structural use in a system (for instance, as a flexural or compressive element). Therefore, timber capacity assessed by applying standard visual strength grading (VSG) procedures intended to be used in the sawmill have some limitations for the prediction of mechanical characteristics of timber load-bearing members on site and their results are generally over conservative, thus leading often to unnecessary demolitions. Adaptation of visual strength grading procedures for on-site assessment first introduced by UNI 11119:2004 standard [10] is discussed in several studies (e.g., [33]) and harmonization documents (e.g., [8]).

Except for proof-loading, which is a direct measure of stiffness, other on-site testing techniques indirectly estimate mechanical parameters. NDT parameters used to characterize structural timbers are mainly based on elastic-wave transmission/vibrational methods, with the NDT variables being the time of flight (TOF)[25] or the natural frequency [34]. TOF measurements are affected by a number of conditions such as the direction of the signal transmission with respect to the wood anatomical directions, and the wood MC [25]. Determination of the dynamic Elastic modulus from the natural frequency relies on a series of simplistic assumptions, such as geometric (prismatic) regularity of a timber member, approximation of its weight and of its boundary conditions. For accessibility reasons, transverse vibration tests are generally preferred (for instance, [34]).

A number of SDT techniques have been proposed for the estimation of mechanical parameters of timber members (see for instance, [24][35]). These techniques either quantify the local resistance of the material against the action of specific probes or directly measure local properties of extracted samples. Major limitations of SDT for the mechanical characterization of timbers are: the lack of standardized procedures and, in many cases, of commercial equipment; sampling criteria, which should consider the local validity of the measurements and the inherent variability of the material; related to the previous point, the necessity of correction factors to apply estimated clear wood properties to full-size structural timbers; reliability of uni- or multivariate empirical models (e.g. regression analysis) linking indirect measurements to inferred properties; and, other factors affecting the relationship between NDT parameter and inferred property (for indirect methods).

[36] propose modification factors for the standardization of non-destructive variables (i.e., TOF, natural frequency, penetration depth, pull-out resistance and drill resistance) taking into account affecting variables such as moisture content, temperature, size/length, and probe position with respect to grain direction.

While most NDT methods are global (involving a large volume of the element), SDT are local measurements. Combination of information provided by two or more independent methods, for instance of a global and a local testing data, in one single model can lead to a more reliable prediction of the property of interest. For instance, [37] suggests combining density data from wood core to improve prediction of dynamic modulus of elasticity (Edyn) using stress wave tests (REF). Additionally, integration of information from visual inspection and NDT/SDT data are proposed to support decision-making processes, for instance using Bayesian methods [38].

### 2.3.Characterization of decay and damage

Due to wood biological nature, timber artefacts can undergo to biodegradation during their service life. An early evaluation of the degrading phenomena is crucial to plan remedial actions and reduce the impact of invasive intervention. Investigations of biodegradation mechanisms, and the influence of changes of wood chemical/physical properties on mechanical characteristics have been subjects of intensive research [39].

During assessment of timber artefacts, evaluation of the occurrence, severity, and nature of decay and damage is a fundamental task that generally starts with visual inspection. Visual inspection enables the detection of wood decay visible on an element surface, however, decay can occur in many hidden segments of timber, such as beam ends buried into masonry. Additionally, early decay is virtually impossible to be detected visually. For these reasons, a series of instrumental techniques can be used to complement visual inspection and more comprehensively characterize decay and damage in timber members.

Also NDT and SDT methods for characterization of decay and damage can be global or local, and result in different levels of resolution [40]. Measurement of drilling resistance is probably the most common and validated technique to detect the presence and extent of decay within timber members, providing high-resolution (typically 0.1 mm) profiles correlated with density variations within the material. In [32] drill-resistance data are mapped within a measuring grid to compare results with stress-wave TOF tomograms to estimate residual cross-sections in decayed timber members [32].

Among the electromagnetic wave-based NDT imaging techniques, digital radiography is readily available, as nowadays various manufacturers produce portable digital X-ray systems. Digital radioscopy has proven to be effective in detecting internal decay and insect attack in timber members, as well identifying construction defects and damage [23][31].

Probably, the most important information to collect for the characterization of decay in timber members are about the triggering and influencing factors (i.e., environmental, constructive, etc.), the type of decaying agents, and if the observed phenomena are active or not. In case of active phenomena or presence of conditions affecting those phenomena, decision should be made, based on prediction of the behaviour of the structure within a specified time frame. Near-infrared spectroscopy and multivariate analysis based on partial least-squares (PLS) has been used to evaluate type of degrading agents and develop prediction models to characterize and monitor decay in timber members [41] and wood surface weathering [42].

### 2.4. From geometrical characterization to structural analysis and monitoring (and closing the loop)

Geometric data is instrumental in supporting various decision-making processes; critical to documentation, preventive conservation and maintenance programs, essential for diagnostic investigation, structural analysis and design of interventions. A thorough representation of the configuration of the structural system aimed at understanding the behavior and the structural role of each component and of the joints is instrumental to the static analysis of a structure, help defining the load paths in timber frameworks and determine critical structural units and elements subjected to greater static demands. Analysis of the geometric data is also fundamental to identify alterations in the structure, such as rigid movements or deformation.

3D geometric data acquisition may be accomplished either through image-based or range-based methods. Availability of 3D data can enhance the production of 3D models and support metrical, structural and technological analysis at different levels of a building and timber structure. This rich 3D datasets can encompass various levels of details, for instance including non-rectangular and varying sections, non-linear beams, out of the plane elements and individual variations of carpentry joints.

NDT imaging methods with different resolution and penetration capabilities, such as radiography [31], GPR [43] , and IR thermography [44], have been successfully used to acquire geometric data of hidden features, such as reinforcements and connections in timber members [31] or timbers concealed by other systems [43][44]. Local SDT, such as drill resistance tests, can provide enriched data on irregular timber cross-sections [45].

The need to develop and use a uniform data model and an exchangeable format to process and communicate metric, non-metric and semantic data is becoming increasingly important. Building Information Models (BIM) and use of Industry Foundation Classes (IFC) as open standard for data exchange are transforming the way geometric data are used in the construction industry, and also in the cultural heritage industry [46]. For the latter, heritage BIM library projects, such as HBIM, provide solutions to integrate and update information from different survey and test methods and use the resulting model as a platform for collaborative data management among different cultural heritage stakeholders [46].

Emerging applications of HBIM systems in heritage management are to support advanced data query off-site and onsite. For instance Virtual Reality (VR) and Augmented Reality (AR) technologies have been applied to the HBIM system to augment expert's access to a building information during on-site risk management, including advanced data query of traditional wooden connections [47].

Advantages of using HBIM platforms for comprehensive structural analysis of traditional timber systems is discussed by [48]. A comparison of structural analysis of traditional timber roof performed with conventional wire-frame models and more complex parametric models showed that the differences in geometry, captured by the parametric model, have a significant impact on the simulation results and are crucial to inform the preservation process [48].

The structural evaluation of existing timber structures presents a challenge due to the necessity to assess the mechanical behavior of timber members and joints, as well as taking into consideration time-dependent variables (creep and load-duration) and biological deterioration. HBIM models can be used as updateable digital replicas of a building or system. While BIM relies mostly on manual update of the model by the users, integration of sensor data into HBIM models can automatize and streamline model update. Implementation of so-called Digital Twin (DT) resulting from the integration of digital models and sensor data holds huge potential for structural assessment and monitoring of historical (as well as new) timber structures. In addition to short-term benefits, such as the possibility to set early-warning, hazard and damage detection systems, long-term advantages include a better understanding of interferences between timber buildings and their environment, and can help buildings' managers evaluating the impact of each implemented technical solution.

## 3. CONCLUSIONS

Holistic assessment methodologies are required to capture the complexity of traditional timber structures, their morphological, technological, material and mechanical variability, and their interaction with the environment. Some of the challenges to effective assessment and monitoring of historical timber structures are due to the scarcity of relevant standards and the lack of a commonly accepted ontological approach, relating scope of the assessment, information required and necessary procedures.

Although seamless data integration and information exchange are key factors for effective assessment and management of historical timber structures, current practice generally follows segmented approaches for each assessment scope and phase, as well as traditional data processing applications, which may not be able to capture the relationships among all the variables affecting the behavior of existing timber structures. This may limit the possibility to turn data into valuable, actionable information.

Multi-criteria tools, data integration and sharing through platforms such as HBIM and digital twins represent promising approaches to support decision-making processes for the assessment and conservation of historical timber structures.

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