Title: Assessment of heritage timber structures: Review of standards, guidelines and procedures.

Short title: Assessment of heritage timber structures: a review

Mariapaola Riggio[1a*], Dina D'Ayala[2a], Maria Adelaide Parisi[3a], Chiara Tardini[4a]

[1a*] Corresponding Author. Oregon State University, Dept. WSE, mariapaola.riggio@oregonstate.edu

236 Richardson Hall, Corvallis, OR 97331, Fax: 541.737.3385, Phone: 541.737.2138

[2a] University College London, Dept. CEGE, d.dayala@ucl.ac.uk

G16b UCL Chadwick Building, Gower Street, London, WC1E 6BT. Phone: 020 7679 7226 (x37226)

[3a] Politecnico di Milano, Dept. ABC, maria.parisi@polimi.it

Piazza Leonardo da Vinci, 32 20133 Milano, Fax: +39.02.23994220, Phone: +39.02. 2399.4334

[4a] Politecnico di Milano, Dept. ABC, chiara.tardini@polimi.it

Piazza Leonardo da Vinci, 32 20133 Milano, Fax: +39.02.23994220, Phone: +39.02. 2399.4334

Abstract

This paper reviews the official documentation (standards, guidelines and procedures) available for the assessment of heritage timber structures. The subsequent discussion does not catalogue all relevant technical literature. Instead, it intends to convey the state of background knowledge, recommendations and code rules using some illustrative examples. A specific focus is given to visual inspection as a fundamental first step for all different scopes and levels of assessment.

The objectives of this review are to: 1) highlight the gaps and limitations in the currently available tools as well as the need for standardization; 2) contribute to the definition of an ontological approach, relating the scope of the assessment, information required and necessary procedures, 3) identify guidance for the different scopes of the assessment.

The variety of timber species, architectural typologies and structural solutions, together with the varied response of these structures to climatic and other natural and manmade hazards, warrant a multifaceted and integrated assessment methodology that accounts for the hierarchical nature of timber structures behaviour and the multitude of agents affecting such behaviour. A review of existing standards and guidelines illustrates the need for a tool to consistently record the assessment process and the final decision taken, which will serve to constitute the knowledge base for the development of the next generation of more integrated and heritage specific guidelines.

Highlights

- A review of the methodological, normative and operational tools for the assessment of heritage timber structures.
- A critical discussion of the gaps and limitations of current assessment tools.
- An introduction to a proposed inspection form for heritage timber roofs.

Keywords

Heritage timber structures; assessment; standards; guidelines; visual inspection.

1. Introduction

Timber is one of the oldest building materials; heritage timber structures are witnesses to a rich tradition of craftsmanship, structural and material knowledge, and sustainable practices (e.g., Figure 1).

The ability to conduct an assessment of the condition of heritage timber structures mandates a deep understanding of their past and current states, including aspects of their conservation, maintenance and use. The motivations for conducting such an assessment can be very diverse; For example, assessment might be required to produce accurate documentation of the structure in order that it be archived for future memory and conservation, or the collection of data from a number of different structures may be aimed at creating the knowledge base for a particular timber construction type. Structural assessment is also the first step towards an intervention that might itself range from mere preservation of an artistic artifact to the full rehabilitation of a structural function, in order to preserve it or adapt it for future use. Each of these situations brings along with it specific needs and formal requirements. While in principle such requirements are not different from those connoted with traditional or historic structures made of other materials [1]; [2]; [3], there are factors specific to timber structures, or of primary importance for the understanding of their behavior, which make their assessment a complex and distinct operation. Such factors are all fundamentally related to the organic nature of timber, as opposed to other construction materials, and while diverse, they are all strictly interdependent in their effect on the structural response of timber structures. For example, material properties and conditions of timber are strongly depend on biological factors and are highly variable. Thus carpentry evolved first on the basis of intuition, and eventually on heuristic and empirical rules, all while depending significantly on region and individual carpenters' knowledge and workmanship. Finally, a timber structure is highly affected by the internal and external environmental conditions it is subjugated to; hence its hygrothermal loading history, which is highly dependent on user habit and local climate, has a fundamental effect on its structural health.

Due to these complexities, a range of experts is generally needed to carry out a thorough assessment of an historic timber structure, encompassing the fields of wood science and technology, structural engineering, architecture, conservation, among others. The availability of assessment and decision tools based on a common ontology, providing a unique, unambiguous and unanimous way of reporting observations and assessment, forms an essential requirement for effective communication and sharing of information in such multi-disciplinary teams.

This paper presents a review of methodological, normative and operational tools which provide the professional knowledge framework which should underpin such decisional tools.

The aims of this review are to a) highlight the gaps and limitations in the currently available tools as well as the need for standardization, b) propose an ontological approach, which relates scope of the assessment, information required and necessary procedures, c) identify guidance available for experts for the different scopes of the assessment.

Figure 2 highlights the relationship between the proposed ontology and the hierarchical framework that regulates the field of structural assessment, broadly corresponding to the hierarchical levels of both the decision-making and the operational process. This same structure is reflected in the organization given to the review carried out in this manuscript. To better qualify and clarify what is intended for each of the levels in the outlined hierarchy, the corresponding definitions provided by the Merriam-Webster dictionary can be taken as reference: a *standard* [4] is defined as "something established by authority (…) as a model (…)", "with quantifiable low level mandatory controls"; a *guideline* [5] is "a rule or instruction that shows or tells how something should be done"; a *procedure*

[6] is referred as “a series of actions that are done in a certain way or order - a particular way of accomplishing something”.

Section 1 introduces the topic of the paper, and section 2 highlights the information and specific steps required in a structural assessment of a historic timber structure. The standards prescribing a specific aspect of the assessment procedure, as well as the guidelines providing instructions for their correct implementation are presented alongside in section 3, for each of the steps identified in section 2. Particular attention is paid to aspects of the assessment procedure that may benefit from enhanced guidance and standardization. Section 4 is dedicated to procedures specifically used for assisting visual inspection of timber structures. An overview of available tools, developed for different applications is presented. Requirements for a multipurpose, multilevel and interdisciplinary visual inspection form, to be used for the assessment of historical timber structures, are discussed and the proposal for a new tool is presented in section 5.

This tool is based on some of the outcomes of the COST Action FP1101 [7], Working Group 1 “Assessment of Timber Structures”, which, through the activity of the Task Group 1 (TG1) “Synthetic methods for the assessment of timber structures” [8]; [9], focused on the development of templates for the inspection of heritage timber roof structures.

Figure 1. Examples of heritage timber structures. Prinkipo Palace (Büyükada, Turkey, 1903) –upper panel- Church of the Guardian Angels (Fermo, Italy, 1871. Arch. G. B. Carducci) – lower panel.

Figure 2. Hierarchical levels of the decision-making and operational process.

2. Assessment of timber structures: rationale – information needed

Assessment of timber structures encompasses different scales of analysis. Heritage timber structures are characterized by a hierarchical organization of systems, units and elements, with connections playing a fundamental role in the load transfer [10] (Figure 3). Features at the different scales of the structure and inter-dependences between the hierarchical levels should be analyzed and data collected in a harmonized manner, for their comprehensive assessment [9]. Various long term experimental, numerical, and analytical research programs have investigated the behavior of timber roof structures also at different hierarchical levels, complementing and quantifying observed behavior [e.g. 11, 12].

The first level of assessment concerns the structure as a whole, its three-dimensional geometry and configuration, in order to ascertain if the structural layout is suitable for its load bearing function, with regard to all possible loading condition the structure is exposed to. At this stage conceptual errors in the structural lay-out and possible missing elements or connections can be identified. When the structure (here referred as structural system) is assembled from a number of similar substructures (here referred as structural unit), as in the case of roofs composed of mainly plane trusses or vertical structures composed of plane frames that are connected transversally with linear elements, the assessment procedure should consider these substructures as a second hierarchical level, where their robustness and the effectiveness and efficiency of their connections determining the load-paths are identified and evaluated. The third level is represented by single structural elements, such as struts, ties, beams or columns. Their geometry and materials, as well as their state of conservation and present damage and decay should be assessed for some or each of them, depending on the level of detail required by the objectives of the study and allowed by the site conditions, prioritizing analysis of the most critical, or potentially vulnerable elements. Finally, carpentry joints, supports, areas of interface with other structures and materials, and connections should be considered, for their configuration, mode of operation and current conditions. The observations, analyses and resulting judgements produced with reference to the lower levels, need to be interpreted systemically to produce a judgment relevant to the whole structure.

Figure 3. Hierarchical organization of a structure. Survey drawings: Courtesy I. Giongo (roof of Rango church), Courtesy G. Massari (survey of a carpentry joint – Thun Castle) [13]

Different operational categories can be identified, defining the type of information required for the assessment, and considering the hierarchy in the structure and the multilevel approach discussed above:

1) Environmental characterization;
2) Identification of the structural system;
3) Identification of alterations to the original structural systems and individual timber members, in terms of:

    3.1) man-made alterations of the original structure;

    3.2) alterations due to unfavorable environmental conditions (i.e., biotic decay);

    3.3) alterations due to the effect of natural hazardous damaging events (i.e., earthquake, flood, hurricane)

    3.4) alterations due to aggressive agents (fire and other chemical agents)
4) Mechanical characterization of the timber structural elements.

The relevance of these four operational categories to a specific level in a structure's hierarchy (Figure 4) can be further summarized as follows:

1) Environmental factors (macro and micro climate) affect the performance of timber structures. With regard to microclimate factors, humidity (i.e., exposure to liquid water or vapor, and consequently, wood Moisture Content - MC) is certainly of major concern for wooden elements. Indeed the hygroscopic nature of wood can lead to dimensional variations of the elements in service, with possible deformations, disconnections or occurrence of internal stresses due to constrained swelling or shrinkage strains [14], resulting eventually in loss of structural integrity and the development of cracks. Moreover, most physical and mechanical properties of the material are affected by wood MC [15]; [16], and the long-term performance of timber elements, both in terms of load bearing behavior (i.e., creep) [17]; [18]; [19] and durability [20]; [21], can be negatively influenced by prolonged exposure to a humid microclimate. As a note related to the rheological behaviour of wood, it is worth mentioning that traditionally, it was very common to build timber structures using green wood; significant deflections can be therefore found in heritage timber structures, as a result of creep of timbers loaded while green.
2) Any construction system is by definition made up of different components. The identification of the structural system aims at understanding the behavior and the structural role of each component, eventually verifying that the system works as a whole [22]; [23]. Analysis of joints is needed in order to clarify how the parts may move and what kind of forces they may transmit with respect to each other. Many heritage timber structures are highly statically indeterminate, thus loads applied to the structure can follow different paths to reach the support. In the definition of the load paths in timber frameworks, a fundamental role is played by carpentry joints [24]; [25]; [26]; [27].

A thorough representation of the configuration of the structural system will support the static analysis of the structure and help determining its critical units and elements subjected to greater static demands. To achieve this goal, a holistic method of assessment is needed. All non-timber elements whose behavior may affect the performance of the timber structure should be included in this evaluation, as well as other timber elements and fixtures that contribute to complete the structure (decorative or accessory) [22]. The supports of the structure should be analysed to evaluate which forces can be transmitted from the structure to its surroundings and vice versa.

3) The identification of alterations in the structure is one the main purposes of the structural assessment. These alterations may result in a structural performance different from what originally intended, and may possibly compromise safety. As outlined above such alterations can take different forms, be caused by different agents and, as Figure 4 shows, occur at each of the levels of the structural hierarchy, resulting in dislocation, permanent deformation, damage or decay. To better appreciate the phenomena involved and the consequences of the observed alterations it is useful to identify the causal action. Different nomenclatures exist for actions and effects on structures (e.g., [28]). For the purpose of this discussion the following definitions will apply. Mechanical damage is here referred to as a consequence of physical, mass and force based actions, i.e., repeated, excessive and long term loading, earthquake, wind, etc. [29]; [30]. It is therefore distinguished from damage due to biotic decay, which is generally, but not exclusively the negative effect of unfavourable environmental conditions [31]. D'Ayala & Wang [32] provide a detailed overview of typical pathologies in Chinese historic temple structures and traditional remedial action used. Chemical damage is the result of the exposure to aggressive agents, including fire [33]. Within this framework, permanent deformations due to creep, plasticity in the material or fatigue and rigid displacement leading to dislocations are the results of one or more combined physical, environmental or chemical actions [34].

4) Mechanical characterization of timber structural elements is required for structural analysis. This implies the estimation of the so-called reference properties (used to define the visual strength grades – density, bending strength and modulus of elasticity), as well as other mechanical/physical properties, such as specific strength capacity, whose quantification is relevant to a specific load condition and structural element.

   Mechanical characterization of timber elements on-site, especially of those that serve as load-bearing structures in buildings of cultural interest, requires the avoidance, or at least the limitation, of removal of authentic material with possible consequent damage to single elements.

   Different, complementary approaches are suggested: proof loading [35], visual strength-grading [36]; [37], and Non-Destructive (ND) [38]; [39]; [40] or Semi-Destructive (SD) measurement of properties [41]; [42]. The application of one or more of the above mentioned approaches depends on the specific case (i.e., type of structure, accessibility, etc.). Different statistical approaches can be used to combine information obtained from different scales and sources, for the prediction of value, variation and distribution of updated parameters [43]; [44]; [45].

A fifth category of data is added to those listed above and related to the “cultural” features of the heritage structure, e.g., the use of traditional crafts, techniques and tools, as well as all the traces of maintenance operations occurred in the course of time. This analysis can be supported by a dendrochronological analysis to date the artefact [46] and comparative analyses with nearby and contemporary structures to identify possible typological correspondences and variances [47].

The categories of data summarized above, are collected at different scales over different extents and by using different procedures. Hence issues of spatial, physical and statistical correlation among the information obtained need to be addressed so that the data collected can be used to produce a holistic assessment of the timber structure under investigation, its elements and its connections.

The different purposes for the assessment can determine the investigation priorities and the relevance of specific information. Some guidance documents [48]; [23] identify three successive levels of assessment with increasing accuracy and detail: a preliminary evaluation of the damage and associated risks, a general investigation of the main structural system, and a detailed, multidisciplinary investigation.

Figure 4. Operational categories for the assessment of timber structures, according to the hierarchical structural levels and the possible levels of the assessment (white fields: preliminary evaluation; light grey fields: general investigation; dark grey fields: detailed investigation – [48]). Figure elaborated from [9]

The ultimate scope of the assessment can also differ from case to case (Figure 5): if the building is of substantial historic or heritage value, then the production of a comprehensive documentation and a condition assessment might be an end in itself. Such condition assessment will support preservation and conservation strategies. More often an assessment is required when the structure is undergoing a change in use or a state of damage comes to light. In such cases full structural analysis, aimed at determining serviceability and ultimate safety margins, is usually undertaken and, depending on the outcome, strengthening provision might be required and designed. Assessment can also be conducted to determine the probability of losses for buildings exposed to specific natural hazards. In this case the objective might be to determine the vulnerability of a specific structure to several perils or to rank several buildings by their expected losses to support decision making in distribution of resources for strengthening and upgrading. Such applications are regulated by national and international standards and tailored to different extent for timber structures by production of specific guidelines. In the following section we offer a review of these documents, aiming at identifying gaps in the present literature and practice.

Figure 5: Procedure/ Level of assessment, quality/Extent of data required and output for different scopes of the assessment.

3. Review of standards and guidelines

The review of available standards, guidelines and other available practice oriented documents is organized in three main classes according to the main purpose underlying the assessment activity: a) Documentation of the building for protection/conservation; b) Vulnerability and damage assessment and c) Analytical assessment for serviceability and safety evaluation. The purpose of the review is to identify specific issues that may benefit from a more focused treatment and standardization.

a. Documentation of the building for protection/conservation

Conservation of timber structures classified as architectural heritage requires collection of data about the features and condition of the architectural asset they belong to. Documentation requirements and protocols vary according to the level of protection (local, national, international). At international level, nomination to and retention of World Heritage status by a building or group of buildings is subject to the production of documentation that describes the present "State of Conservation and factors affecting the properties", including "manmade and environmental pressures", natural hazards, etc. Semplici [49] points out that the UNESCO nomination form does not explicitly require a technical documentation including structural failures with identification of causes and effects, which would be the first step to the design of appropriate conservation strategies. A notable exception is represented by the listing of the whole wooden log churches of the Carpathian Region in Poland and Ukraine [50].

Two Scientific committees within the ICOMOS organization are directly relevant to the documentation and structural assessment of timber structures: the ISCARSAH committee and the International Wood Committee (IIWC). The first devotes its work to the Assessment and Restoration of Structures of Architectural Heritage, the second is the ICOMOS Wood Committee. Both committees have produced Principles and Guidelines. The IIWC charter, entitled "Principles for the Preservation of Historic Timber Structures" [51] was adopted by ICOMOS in the 1999 General Assembly. ISCARSAH Principles [52] were adopted by ICOMOS in the 2003 General Assembly. Both documents recommend inspection, recording and documentation and advocate the important principle that diagnosis and intervention should follow attentive and thorough study of present and past conditions. Both documents recommend levels of investigation which go beyond the so-called "desk survey" [23], generally performed for documentation tasks. Indeed, some of the analyses illustrated in the ICOMOS guidelines are appropriate for safety and serviceability evaluations, as further discussed in the section "c" of this review. However these documents provide no advice in terms of the demand actions or the performance conditions in response to such actions that the structures should satisfy in order to comply with safety and serviceability requirements.

As statements of principles these documents have represented important milestones at the turn of the millennium, however they do not provide guidance or specific instructions as to the level of depth or extent to which such activities should be taken, or the way in which the data collected should be organized and analysed, in relation to the purpose of the assessment conducted.

While generally attention is paid to the structural components, protection and conservation of a heritage building involves the analysis of the different elements which characterize its authenticity [53]; [54]; [55]. Accordingly decoration, coating and complementary components should be documented and included in the assessment procedure. The *Standards and Guidelines for the*

Conservation of Historic Places in Canada [56] draws attention to "(…) the form, type, and color of coatings such as paint; and the condition of exterior wood features (…)". A revision of the IIWC Principles proposed in 2016 [57] goes further and lists among the elements to be reported during the inspection and survey of the artifact also the "invisible" marks, i.e., those marks used by carpenters during construction or subsequent works, which are not intended to be visible features of the structure.

b. Vulnerability and damage assessment

Vulnerability of timber structures can be related to different natural and man-induced hazards, e.g., earthquake, hurricanes, floods, fires, etc. Vulnerability assessment correlating recurring damage to specific structural systems and specific hazards has as ultimate objective the reduction of damage risk by damage prevention. Typically vulnerability studies are conducted at large scale, with the purpose of determining the losses due to the probability that a hazardous event of a given magnitude would affect a population of buildings exposed to it and characterised by a probabilistic level of fragility [58]. Vulnerability studies are particularly developed for seismic hazard affecting masonry building typologies, which have proven time and again to be very vulnerable and the major contributor to life loss in earthquake prone areas. For a comprehensive overview of vulnerability assessment methods for historic buildings subjected to seismic hazard the reader is referred to [59]. The geographic information system-based multi-hazard (MH) analysis tool, HAZUS MH, developed by the Federal Emergency Management Agency (FEMA) [60]; [61] is currently the most comprehensive framework including earthquake, flood and hurricane hazards and applicable to a wide range of structural typologies. HAZUS MH [60] indeed provides fragility functions for two basic timber structural typologies, residential light frame and commercial timber framed buildings. None of these two typologies is directly applicable to European historic timber buildings, for instance. Moreover HAZUS

MH [62] also provides a performance based analytical procedure for determining the probability of failure of timber roof structures subject to hurricane force winds, specifically the probability of losing the roof cover due to pull-out or pull-over failure of the nails or connectors. Although for the purpose of HAZUS this procedure is only validated for modern structural assemblies relevant for the U.S. typologies, D'Ayala et al. [62] have recently shown its applicability to the timber roofs structures of historic masonry churches built in the Philippines, using Spanish colonial technology.

The only guidance document entirely dedicated to the assessment and retrofitting of timber structures, to our knowledge, is the FEMA 807 "Seismic Evaluation and Retrofit of Multi-Unit Wood-Frame Buildings with Weak First Stories" [63], which focuses on a specific structural type particularly common in California. Many of these 3 to 5 storeys residential buildings, built in the pre-code era, were damaged during earthquakes in the late 20th century and the many surviving ones, need retrofitting to prevent soft storey collapse mechanisms. In line with other assessment standards, such as ASCE 41-13 [3], FEMA 807 recommends first a simplified and then a detailed evaluation, both aimed at determining the difference in lateral capacity between the ground storey and other storeys, and hence the need for retrofitting.

c. Analytical assessment for serviceability and safety evaluation

Analytical assessment for serviceability and safety evaluation is required when a change in the use of a building is planned, in case of evident or suspected alterations, and to inform any intervention on a structure. General structural codes seldom treat existing timber structures, or assessment. Design codes, such as the Eurocode 5 [64], covering new structures design only, adopt a conservative approach involving the application of safety factors, to take into account the various uncertainties that can be expected both on the resistance and load effect over a preset service life. However, such an approach is not appropriate in heritage structures where requirements to improve the strength may lead to the alteration of the original structure.

At international level, ISO 13822 “Bases for design of structures -- Assessment of existing structures” issued in 2010 [2] is intended to serve as a basis for the development of national standards. It deals with structural safety and cost saving but it is not structure-material specific, and does not provide conservation criteria. The approach is to perform the minimum effective intervention, in order to limit excessively invasive ones, often used in the past, that have shown to be less satisfactory than expected in terms of performance. This standard identifies different analysis levels depending on the sequential results of the assessment (i.e., preliminary assessment followed, if necessary by detailed assessment and periodical inspection). In case of suspected/altered conditions the standard recommends a detailed assessment, including structural analysis. The existing structure should be verified to ensure a target reliability level (in agreement with recommendations provided by ISO 2394: 2015 [65], which represents the required level of structural performance.

An *ad-hoc* working group (WG2) within the Technical Committee CEN/TC 250 “Structural Eurocodes” has been established to address the need to bring together different national approaches to the assessment and retrofitting of existing structures. This activity has resulted in the publication by the European Commission’s Joint Research Centre (JRC) of “New technical Rules for the Assessment and Retrofitting of Existing Structures” [66]. This document is a brief summary of National Technical Codes of European Countries dedicated to existing structures. Part II is a detailed overview of the existing National Regulations and Standards in twelve European Countries. Besides those standards generally addressing the assessment of existing structures, some national codes refer also specifically to timber structures. Among these, the Czech Republic standard --first issued in 1986 [67]-- on “Assessment and verification of existing structures – Supplementary guidance" treats existing timber structures and is mainly based on ISO 13822.

The Italian National Design Code, NTC2008 [68], provides some very general principles about conservation of timber roofs and timber floor slabs for traditional buildings in seismic areas. Indications for the necessary prior assessment are not given.

The Swiss Code, SIA, has a document devoted to the assessment of existing structures, with a section (part 5) on timber structures [48]. The Code is divided in seven parts: a general part about the examination of the structure, its monitoring and maintenance; a second one about use requirements, structural safety, serviceability and effectiveness of maintenance interventions. Then the code includes a section describing methods to update available information related to actions, material properties, geometrical properties, load carrying and deformation behavior and degradation mechanisms. According to the code, updating of these data can be done either i) using Bayesian techniques for individual random variable measured or observed, or ii) considering conditional failure probabilities due to measured/observed variables (e.g., cracks, etc.) or expected variables (e.g., extreme loads, etc.) [69]. Once the current conditions are established, a so-called "posterior probabilistic design" can be carried out. The part dedicated to the structural analysis and verification is followed by a part on the examination, which details procedure, condition survey and evaluation and the recommendation for maintenance interventions. Annex C provides indications and tools to carry out an accurate geometric survey in order to achieve a good knowledge of the state of health of the structure. The more extensive and deeper is the structural inspection, the better is the knowledge that can be obtained: a limited knowledge can be obtained if less than 50% of the structure is examined, a normal knowledge if the inspection extends between 50% and 80%, a complete knowledge is the outcome of more than 80% of the structure being inspected. Tools and techniques that can be adopted for this purpose are indicated in table 3.1 of SIA 269/5:2011 [48]. These inspection requirements are much more demanding than for instance, the requirements for assessment of steel or concrete structures as outlined by Eurocode 8 [70] or ASCE 41-13 [3], to achieve the same level of knowledge. This extra inspection burden reflects the greater variability observed in existing timber structures. Table 4 of SIA 269/5 defines decay and damage that can occur in connections. Eight different connection typologies are listed and for each of them the most recurring decay and damage are reported. No quantitative directions for an actual evaluation of the state of conservation are given neither in table 3 nor in table 4 of the Swiss code.

While the standards cited above refers in general to “existing structures”, ICOMOS guidelines [51-52] are explicitly devoted to heritage structures, for which a more careful approach is required, to ensure that intervention preserve the actual structural behaviour and comply with the principle of minimum intervention. According to ISCARSAH guidelines, safety evaluation is based on an evaluation of the results obtained from three diagnostic procedures: historical analysis (i.e., as a basis to interpret current behaviour and forecast future performance), qualitative (or inductive) approach and quantitative analysis (which includes both the analytical and the experimental approach). In the document, limited applicability of quantitative analysis for heritage structures is clearly highlighted.

In 1996 a working group, so-called UNI Normal GL20, was established by the Italian Standardization Institute (UNI), to address specifically the analysis and conservation of heritage timber structures. [71]. From the activity of the UNI Normal GL20, relevant standards have been issued to define assessment at the level of the timber structural element, including the characterization of the material and its properties. UNI 11161 [72

] gives general guidelines regarding different levels of action on heritage timber structures from conservation, to restoration and maintenance. UNI 11138 [22] focuses mainly on interventions. The first part of this document develops the necessary preliminary analysis of the artifact, including tasks like historical analysis and structural analysis.; UNI 11119 [73], is specifically devoted to inspection for diagnostics, based on the following information: a) wood species (which should be identified according to UNI 11118 [74]); b) wood moisture and moisture gradients c) class of biological risk, according to CEN EN 335 part 1 and 2 [75]; d) geometrical features, including, position and extension of heterogeneities (i.e., defects) and alterations e) position, shape and dimension of critical zones and critical sections, as defined considering both defects and alteration occurrence and loading conditions) f) visual strength grading that, in the case of existing structures, considers the relevance of the strength affecting features for actual static conditions (type of structural element and loading mode).

Mannucci et al. [76] present the experience collected in the first years of use of UNI 11119 standard, including some interesting hints for its improvement, such as the necessity to adopt criteria to detect decay in the inspected elements as well as to analyze the role and conditions of the joints.

The applicability (and limitations) of criteria established in UNI 11119 standard, to characterize timber elements in historical timber structures in geographic contexts other than Italy has been discussed by a number of authors [77]; [78].

The American standards for in-situ grading of structural timber in existing structures is ASTM D 245 [79]. A detailed discussion on the applicability and limitation of this standard to grade timbers in historic structures is provided by Anthony et al. [37].

At the European level, activity of a number of COST Actions has significantly contributed to development of documents addressing specifically timber structures.

The "Guidelines for the on-site assessment of historic timber structures" [23] developed within the COST Action IE0601, provide principles and possible approaches for safety assessment of existing timber structures. The Guidelines refer to ISO 13822 [2], and to the result of a previous COST Action, E55, on the assessment of timber structures [80]. The latter document, based on a probabilistic approach, considers the assessment as a regular operation in the life of timber structures, without specifically distinguishing historical from more recent ones. The Guidelines divide the assessment in three phases: a preliminary phase with a first survey and a structural analysis, a second phase devoted to a detailed field survey including the categorization of members according to the main action stress resultant and the elements' strength grading, based either on visual methods or ND testing. It is worth to mention that the document refers to the criterion of the critical cross section, for visual grading existing timber elements, as described in the UNI 11119:2004 [73]. Limitations of on-site visual grading, such as unavailability of "strength profiles" for typical traditional scantlings, are also discussed in the document. The third and final phase of the detailed survey as referred in the guidelines relates to the assessment of joints. The three phases of the document correspond well to the hierarchical levels of assessment outlined in section 2 of this manuscript. Although the Guidelines associate specific operations to each phase, further development and standardization is needed for each of them, as for instance in the case of visual inspection, which pertains to phase 1.

The European Committee for Standardisation (CEN) established a new Technical Committee CEN TC 346 in 2004, to deal with "Conservation of cultural property". The aim of the CEN TC 346 is the

> "standardisation in the field of definitions and terminology, methods of testing and analysis, to support the characterisation of materials and deterioration processes of movable and immovable heritage, and the products and technologies used for the planning and execution of their conservation, restoration, repair and maintenance" [81].

In 2012 a new working group (WG10) was established in the CEN TC 346, to deal specifically with the assessment of historical timber structures. CEN TC 346- WG10 has adopted the Guidelines developed by the COST Action IE0601 as a base document for the preparation of a pre-standard document for the assessment of historical timber structures. In 2017 the prEN17121, developed by CEN TC 346 - WG10, was sent to the standardization bodies for the public enquiry. Table 1 summarizes the selection of codes and guidelines that deal with timber structures, of which only a few treat existing structures and only the COST Action IE0601 Guidelines directly addresses assessment.

Table 1. Comparison of Standard and guidelines

4. Procedures for visual inspection

Visual inspection is the basis of any assessment procedure, intended to provide information about the soundness of a construction, as shown in Figure 5. It requires no equipment except the naked eye of a trained inspector. The first step of visual inspection consists in a global, preliminary check, by conducting an initial walk-through, to evaluate the general conditions of the structure as a whole. Good accessibility, with scaffolding and proper lighting, should be provided in order to get as close as possible to the timber elements; Here, a more detailed geometric and mechanical survey of the timber elements aims at evaluating the presence and relevance of alterations (i.e., decay, damage, deformations) and strength-affecting natural defects. Visual inspection is also a basis for the mechanical characterization of timber elements, following the visual strength grading approach. A detailed description of the different steps of visual inspection of timber elements, as described in UNI 11119, has been included in the recommendations developed by the RILEM Technical Committee AST 215, for the in situ assessment of timber structures [38].

During visual inspection, qualitative data about the characteristics and condition of the structure can be collected and systematically recorded using templates. Such templates are generally developed on an ad hoc basis and don’t reflect format and content unanimously shared among the professional community. Templates are not substitute of experience; they have to be used by experts, and ideally should provide a common, shared framework and knowledge base, to collect and exchange information for the different professionals involved in the assessment. The lack of a common, unambiguous way of defining structural types and damage is one of the main barriers for an effective communication among experts. For this reason, diverse technical committees (e.g., ICOMOS IWC [51]; COST IE0601 [23]; COST E55 [80]; UNI Normal GL20 [71]; CEN TC 346- WG10 [82]; COST FP1101-WG1-TG1 [8]) are contributing to the effort of defining a generally accepted procedure for the implementation of visual inspection of existing timber structures. This implies the definition of a general taxonomy to describe timber structure types and related features and involves identifying a unique, unambiguous and unanimous way of collecting and representing information needed for visual inspection.

In most cases, these efforts have resulted in the development of guidelines. While guidelines offer a certain degree of versatility and can be adapted to a number of contexts and building types, the procedures suggested by structured forms are more constrained and contextual (or building-specific), thus limiting their applicability to a smaller set of situations. Among the advantages related to the use of specifically structured forms and templates during inspection is a more homogeneous evaluation, even if performed by different professionals, which helps to point out the most significant aspects and critical situations in a calibrated way.

The development of procedural forms is complicated by two main requirements: the necessity of a) managing the inherent variety of the objects of interest (e.g., timber structures) and; b) addressing different scopes of the assessment.

To meet the first requirement, a procedure needs to define “typological categories” for the inspected objects. This means, in the case of historical timber structures, to incorporate and bridge over the “variations on the theme” (i.e., regional, historical and individual variations) which often alter canonical forms [47].

The different ways procedures are constructed, depending on their specific application, is discussed in the following section, which focuses on the corresponding inspection form. In this review, we have included tools that have not been conceived for timber structures, but have been used as a basis to develop forms specifically addressing timber structures.

a. Inspection templates for vulnerability and damage assessment

Structured templates have been used extensively for conducting visual inspections, with the intent of assessing the state of a structure, particularly in terms of seismic vulnerability and seismic damage. Amongst these templates, different kinds of buildings and structures have been covered, including, some templates for timber structures, e.g. the ASCE 41-13 [3] document. The ASCE 41-13 Tier 1 lists items to be checked and evaluated according to a given scale. The relevant structures are, once more, modern structural types, not directly applicable to the cases considered here.

A well-defined form or template is crucial for a successful data collection campaign. The template guides visual analysis, focusing attention on the items that are most critical or most useful for the specific purpose at hand.

A recent research program--within the activity of the Italian Civil Protection Department (DPC)--has addressed the case of different layouts of heritage roof structures, which can highly influence the seismic response of the respective building. A procedure for assessing their seismic vulnerability has been outlined. It comprises a form-based visual inspection from which different characteristics like the structural type, the condition of the roof supports, the effectiveness of joints, and the maintenance state are graded to assess the vulnerability level [83] (Figure 6). Beyond the seismic problem, this kind of tool may be useful to support professional practice as well as to produce a significant increase of knowledge on existing timber structures.

Figure 6. Example of forms for seismic vulnerability assessment of historical timber roofs (M.A. Parisi, C. Tardini).

Post-event procedures for the fast assessment of damage also rely on the inspection of the building and the analysis of a series of elements along a predefined data collection form. The widely used ATC-20 procedure (issued originally in 1989, with the most recent revision in 2005), is implemented in a series of forms to be filled out in a field survey [84]. Two levels are proposed in ATC-20: a "rapid screening" and a so-called "detailed screening". In the latter, the single-page form requires one to declare the type of building associated with the material (e.g., timber building), as well as which elements are damaged (slabs, columns, etc.) and to what extent. Inspection is to be performed in one hour or less. The result is associated to a color-coded placard to be posted on the building, declaring it as "inspected" (and considered safe), of "limited access", or "unsafe".

The RVS (rapid visual screening) procedure proposed by FEMA [85] is intended to assess the seismic risk for buildings for preventive purposes. In Appendix B the document reports the data collection forms, which are specific and detailed for different structural types, and which cover various types of wood frame buildings.

An example of a template for seismic damage assessment is the AEDES form [86], which is used in Italy to perform a first survey of damaged buildings of any construction material to determine whether a building is usable, in need of repair or a threat to safety.

In the period intervening between the Umbria Marche earthquake of 1997 and the L'Aquila 2009 earthquake, the Italian Ministry for Architectural and Cultural Heritage, in collaboration with the Civil Protection Department, developed two templates aimed specifically at heritage buildings: one for churches and one for palaces. The template A-DC PCM-DPC [87], for churches, contains information about the current state of the building and compound, secondary hazards, location and geometrical data. The seismic damage is codified in terms of possible collapse mechanisms, collated in a damage-type list, and the surveyor is also required to provide details of the extent of damage to decorative finishes and artwork. The template B-DP PCM-DPC [88], for palaces, has a similar structure and the damage is also associated to specific collapse mechanisms, including failures of timber floors and roofs.

Following the 2010 Haiti earthquake, an attempt was made by ICOMOS Haiti with the support of ICOMOS ISCARSAH to adapt the AEDES template to the specific characteristic of Haiti architectural heritage, which comprise large numbers of timber structures [89]. The form is presented in Figure 7, as an example of damage assessment template.

Following the 1999 ChiChi Taiwan earthquake, many historic temples were damaged or collapsed. D'Ayala and Tsai [90] proposed a survey template to determine type and extent of damage and a performance based analytical assessment framework which would enable decision making as to the requirement and extent of any strengthening [91].

Periodic inspection of vulnerable, strategic structures is a fundamental practice to reduce risks and optimize asset management planning. Periodic inspection of transportation infrastructures, such as bridges, is a typical case where the need of a standardized reporting model is necessary, in order to effectively collect, analyse and compare data from different sources or inspection periods. In this regard, it is worth mentioning the effort of the Slovenian National Building and Civil Engineering Institute - ZAG, which developed for the Slovenia Roads Agency – DRSC, a bridge inspection procedure

(Ebridge) [92]; [93]. The developed software addresses all kinds of bridge structures, and has been extensively used to inspect a number of timber bridges in the country.

Increasing digitalization of data and rapid development of portable digital implements, such as smartphones and tablets, motivates the switch from the traditional paper form to digital forms on mobile devices. Within the Mondis project [94] a tool for on-site monitoring of monument damage using mobile devices has been developed. The tool uses a knowledge-based system built on top of an ontological framework (Monument Damage Ontology).

Within the PERPETUATE (Performance Based Approach to Earthquake protection of Cultural Heritage in European and Mediterranean Countries) FP7 project, Novelli & D'Ayala [95] have developed Log-IDEAH, which is a logic tree decision system freely available on the internet and usable on both Android and iOS platforms; This allows the user to record topology and damage patterns on buildings' facades and to interpret these using an expert trained knowledge system, helping determine possible failure modes and inform safety shoring and repairs.

Figure 7. ICOMOS post-earthquake damage assessment – Haiti 2010 (Courtesy Kelley, S. J. and Sparks, S. P., 2010)

A procedure for the systematic data collection and vulnerability assessment of historic structures--encompassing masonry loadbearing walls and timber roofs and floors structures-- was developed initially by D'Ayala & Speranza [96] in order to determine the prevalent collapse mechanisms and load factors of buildings in the earthquake prone region of central Italy. The FaMIVE (Failure Mechanism Identification and Vulnerability Evaluation) procedure, was designed from the beginning as a flexible data collection platform, and it has since been extended to suit heritage structures in different part of the world, from Turkey to India and Nepal. More recently a new version has been adapted to cater for heritage churches in the Philippines, hit by the Bohol earthquake. As part of this work, a specific set of parameters has been developed to allow documentation of the roof trusses of those churches and to determine their seismic response [62] (Figure 8). The same parameter-set is also used to determine the roof vulnerability to wind loading.

Figure 8. Data collection form for roof truss systems, within the FaMIVE procedure [62]

The need for a specific focus on the performance and reliability of timber structures is relatively recent, and mainly motivated by the increasing use of engineered wood systems in large span structures.

At the beginning of 2006 some contemporary timber structures in Europe collapsed [97]; in most of these cases failure occurred under snow load, and evidently due to some vulnerabilities inherent to the structures. The need to acquire a systematic knowledge from these incidents motivated a number of investigation campaigns and the development of a structured inspection form for damage classification [98]. The failure assessment template for timber structures, developed in the framework of the Cost Action E55 [97]; [98]; [99], is based on a comprehensive survey and analysis of those failures reported on contemporary timber structures in North and Central Europe. The approach proposed for the failure assessment of contemporary, engineered timber structures is not straightforwardly applicable to heritage structures. The main reason for this is the lack of specific historic standards that can be taken as reference for the design and construction of historic timber structures, and hence determine their lack of compliance.

When dealing with historic constructions, some specific considerations have to be made: a) documents of the original design and, in some cases, of subsequent interventions are often missing; b) design criteria are based on consolidated practice, instead of design codes; c) it is often difficult to include a structure into a general category, because of a number of variations at the different scales (from the overall structural configuration to detailing), occurring in different geographic and historic/cultural contexts; d) the “historic” material is generally massive wood, which is characterized by a high variability, among elements of the same wooden species in a structure, and even within a single element.

For the reasons listed above, the adoption of a general approach that is valid for both contemporary and historical timber constructions is generally not feasible. For the same reasons, most of the available operational tools for the inspection of historical timber structures have been developed by practitioners and experts on the basis of specific case studies and applications (e.g., [100]; [10]; [101]). These documents are mainly based on the authors’ experience, and can be a precious source of information for the passage from general principles to practical applications. The procedure developed by Tampone [10] is based on a hierarchical order beginning from the analysis at the structural level to the analysis of each single element and finally to connections. This approach has also been used for the inspection template presented in the following section.

The EN 844 standards provide guidance for an unambiguous definition of wood material features and alterations due to biotic decay [102]. A definition of structural failures and damage in timber structures has been recently proposed by Tampone [28]. However, in many assessment reports produced by experts the distinction between material and structural alterations and their causes is not clearly made. Also, some authors (i.e., Ross [100]) refer to both the alterations and their causes as defects. Ross, in contrast to others, also includes noise transmission and vibration of floors in the range of possible defects to investigate during the inspection of timber structures [100] although these are phenomena not necessarily caused by defects of the structure inspected but which identify possible limitations of use.

Table 2. Synoptic table of official inspection tools for existing structures

Table 3. Assessment tools for timber structures – literature review

5. A multipurpose inspection template

The previously mentioned inspection forms available for timber structures, reviewed in the previous section, neither address all the different scopes of the assessment nor the various historical structural types.

The development of more general inspection templates for the assessment of historical timber structures has been the main aim of the task group 1 – TG1, COST Action FP1101-WG1 [8]. The scope of these templates is twofold: first to serve as an operational tool for the professional community, to guide the expert in the collection and interpretation of data during inspection (both periodical inspection and post-event); second, to create a consistent database of timber structural types, as well as relevant, recurrent damages and identifiable causes, to be accessible for the scientific community.

Despite the general aim, the template has been refined and deployed so far to specifically address timber roof types typical of European historical assets. The choice to focus on timber roofs is motivated by their presence and survival in historic constructions, even in those where other materials were used for other structural systems. Given the richness and variability of roof types in different geographic and cultural contexts, the template is designed to be flexibly altered to suit different construction types. Currently, to our knowledge this template represents the most exhaustive and structured tool for the inspection and damage assessment of traditional timber systems.

The template is implemented in a database management system (MS Access) according to a tree-like organization [9], which reflects the typical hierarchy in timber structures (i.e., building, primary and secondary systems, units, members and connections (as described in Figure 3). A general description of the inspected object (at the different levels) includes structural type, geometry, historical information, service conditions (Figure 9 – upper panel). A section is dedicated to the description of damage. This includes relevant hierarchical level, type of damage effects (in terms of failure modes, rigid movements or deformations), state (i.e., "active" or "non-active", or "intervened on", at the time of the inspection), and role ("primary" or triggering damage, "secondary" or subsequent damage) (Figure 9 – lower panel).

In case of an incorrect practice, inspection reports account only for damage effects, without inquiring their causes, or, as we have discussed in the previous section, in some reports there is not a clear distinction between effects and causes.

In the implemented template, the causes of primary damage have been explicitly identified and grouped in six classes (poor design, poor construction, material degradation, poor maintenance, interventions and extreme actions). The template allows to record not only occurred damage, but also unfavorable conditions, which can cause damage in the future.

The template supports the different levels of the assessment (as described in Figure 5). For the detailed assessment of timber elements, a description of so-called defects (i.e., strength-affecting material macroscopic features, such as knots) is required. This information, should be collected according to a relevant (if available) standard for that wooden species, to allow subsequent assignment of an element to a strength class. In its current form, the template does not permit to incorporate data from ND or SD tests, in order to complement visual strength grading or to quantify the observed damage. An extensive validation of the form is currently on-going, with the aim of evaluating adaptability to different case-studies, flexibility and ease of use, and impact on inspection procedures, as described at the beginning of this section.

Figure 9. "Inspection template for the assessment of historic timber roof structures" (Courtesy A. Serafini)

Upper panel: Analysis of geometry, typology and material characteristics. Level of the structural unit.

Lower panel: Assessment of damage. Level of the structural element.

6. Conclusions

This paper reviews a number of methodological, normative and operational tools, with the aim to provide professionals and researchers with a knowledge framework for the assessment and conservation of heritage timber structures.

An ontological approach has been proposed, to relate scope of the assessment, information required and necessary procedures.

One of the main objectives of this review was to highlight gaps and limitations in the currently available tools.

From data exposed in Tables 1 and 2, it may be concluded that a number of standards and guidelines are available to guide experts in the assessment of timber structures. These standards function either to define the level of vulnerability or damage, or for safety and serviceability checks and consequent design of interventions. However, at a closer look, it is evident 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.
- Standards dealing with a detailed level of inspection are available only in few countries (e.g., Italy). They are mainly focusing on the inspection of timber systems and elements (i.e., structural timber), while few or no indications are given with respect to timber connections.
- The Swiss standard SIA 265/5:2011 and the guidelines developed within the COST Action IE0601 are to date the only available documents that consider the different levels of the investigations and hierarchical levels of the structure. When lacking more specific procedural indications, these documents can be used to develop inspection forms.
- The inspection form developed within the COST Action FP1101 intends to fill the gap between the guidelines and the more detailed steps to follow in the praxis.
- In the inspection form introduced in this paper, a comprehensive taxonomy has been defined to describe timber structures and damage phenomena in an unambiguous way. However, it should be noted that the tool has still been developed only for a category of traditional timber structures (roof) and the taxonomy (and related glossary) is valid only for a determined, even if broad, geographic area.
- While we believe that it is not possible, or advisable, to perform a generalization of the specific information necessary to properly describe each structural type and the related damage (and therefore develop a theoretically “globally-applicable” inspection form), we see a necessity of using a comparable ontology, to develop forms applicable in different contexts and for different scopes of the assessment.

Hopefully the knowledge base that will be developed by consistently recording the assessment process and final decision of cases examined will be available to support the development of future codes and guidelines that are more integrated and heritage specific.

Acknowledgments

COST Action FP1101 – Working Group 1 (WG1) "Assessment of Timber Structures" has contributed to the development of the inspection template discussed in Section 4 of this paper. Special thanks go to Eleftheria Tsakanika, who led the activity of the Task Group 1-WG1. The template has been implemented by Anna Serafini, University of Strathclyde, during a Short-term Scientific Mission (STSM) at the CNR-IVALSA, under the supervision of Mariapaola Riggio. The STSM was funded by COST Action FP1101 (COST-STSM-ECOST-STSM-FP1101-180515-058826).

Partial financial support by Re.L.U.I.S. DPC program is gratefully acknowledged by Maria Adelaide Parisi.

References

1 International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage ISCARSAH (2014) Recommendations for the analysis, conservation and structural restoration of architectural heritage.

2 ISO 13822:2010, Bases for design of structures – Assessment of existing structures

3 ASCE 41-13, (2013), Seismic Evaluation and Upgrade of Existing Buildings, American Society of Civil Engineers, Reston, Virginia.

4 "Standard." *Merriam-Webster.com*. Merriam-Webster, n.d. Web. 25 Apr. 2017.

5 "Guideline." Merriam-Webster.com. Merriam-Webster, n.d. Web. 25 Apr. 2017.

6 "Procedure." Merriam-Webster.com. Merriam-Webster, n.d. Web. 25 Apr. 2017.

7 D'Ayala, D., Branco, J.M., Riggio, M., Harte, A., Kurz, J., Descamps T. (2015). Assessment, reinforcement and monitoring of timber structures: FPS Cost Action FP1101. SAHC2014–9th International Conference on Structural Analysis of Historical Constructions.

8 Riggio, M., Parisi, M.A., Tardini, C., Tsakanika, E., D'Ayala, D., Ruggieri, N., Tampone, G., Augelli, F. (2015). Existing timber structures: proposal for an assessment template. 3rd International Conference on Structural Health Assessment of Timber Structures. Wroclaw, September 9-11, 2015

9 Serafini, A., Riggio, M., González-Longo, C. (2016). A Database Model for the Analysis and Assessment of Historic Timber Roof Structures. International Wood Products Journal. http://dx.doi.org/10.1080/20426445.2016.1232929

10 Tampone, G. (1996). Il restauro delle strutture di legno. Hoepli eds. (in Italian)

11 Branco, J.M., Piazza, M., Cruz, P.J.S. (2010). Structural analysis of two King-post timber trusses: Non destructive evaluation and load-carrying tests. Construction and Building Materials 24; 371-383

12 Parisi, M.A., Piazza, M. (2002). Seismic behavior and retrofitting of joints in traditional timber roof structures. Soil Dynamics and Earthquake Engineering 22; 1183-1191

13 Massari, G., Riggio, M., Gadotti, F. (2010). "Respecting the Diversity". The Timber Roof of the “Cannons Loggia” in the Thun Castle (Italy). Advanced Materials Research Vols. 133-134: 1107-1112

14 Fragiacomo, M., Fortino, S., Tononi, D., Usardi, I., Toratti, T. (2011). Moisture-induced stresses perpendicular to grain in cross-sections of timber members exposed to different climates, Engineering Structures 33 (2011) 3071–3078.

15 Gerhards, C.C. (1982). Effect of moisture content and temperature on the mechanical properties of wood: an analysis of immediate effects. Wood Fiber, 14 (1): 4-36

16 Glass, S.V., Zelinka S.L. (2010) Moisture relations and physical properties of wood. Wood handbook: wood as an engineering material. FPL USDA: 4.1-4.19.

17 Barrett, J.D, Foschi, R.O. (1978). Duration of load and probability of failure in wood. Part 1: modelling creep rupture. Can J Civil Eng 1978; 5(40):505–14.

18 Fridley, K.J, Tang, R.C., Soltis, L.A., Yoo, C.H. (1992) Hygrothermal effects on load-duration behavior of structural lumber. Journal of Structural Engineering. 118 (4): 1023-1038

19 Rosowsky, D.V., Bulleit, W.M. (2002). Load duration effects in wood members and connections: order statistics and critical loads. Structural Safety 24(2–4):347–62.

20 Isaksoon, T., Thelandersson, S., Ekstrand-Tobin, A., Johansson P. (2010). Critical conditions for onset of mould growth under varying climate conditions. Building and Environment 45: 1712-1721

21 Pilt, K., Teder, M., Süda, I., Noldt, U. 2014. In-situ measurement of microclimatic conditions and modeling of mechanical properties of timber structures − a case study on new church on Ruhnu Island, Estonia. – International Biodeterioration & Biodegradation, 86, 158−164

22 UNI 11138:2004, Cultural heritage - Wooden artefacts - Building load bearing structures - Criteria for the preliminary evaluation, the design and the execution of works. UNI (Ente nazionale italiano di unificazione) (in Italian).

23 Cruz, H., Yeomans, D., Tsakanika, E., Macchioni, N., Jorissen, A., Touza, M., Mannucci, M., Lourenço, P.B., (2015) Guidelines for On-Site Assessment of Historic Timber Structures, International Journal of Architectural Heritage, vol. 9, (3): 277-289

24 Parisi M.A., Piazza, M. (2000). Mechanics of plain and retrofitted traditional timber connections. Journal of Structural Engineering, 126 (12): 1395-1403.

25 Larsen, H., Jensen, J. (2000), Influence of semi-rigidity of joints on the behaviour of timber structures. Prog. Struct. Engineering Materials, 2:2767–2778

26 Šobra, K., Ferreira, C.F., Riggio, M., D'Ayala, D., Arriaga, F., Aira J.R. (2015). A new tool for the structural assessment of historic carpentry joints. 3rd International Conference on Structural Health Assessment of Timber Structures. Wroclaw, September 9-11, 2015

27 Branco, J.M., Descamps, T. (2015). Analysis and strengthening of carpentry joints. Construction and Building Materials 97:34-47

28 Tampone, G. (2016) Atlas of the failures of timber structures. Nardini, Florence.

29 Frangopol, D.M., Curley, J.P. (1987). Effects of damage and redundancy on structural reliability, Journal of Structural Engineering, 113:1533–1549

30 Sørensen, J.D. (2011) Framework for robustness assessment of timber structures, Engineering Structures, 33 (11): 3087–3092

31 Ridout, B., (2000), Timber decay in buildings. The conservation approach to treatment. E & FN Spon, London

32 D'Ayala, D., Wang, H. (2006). Conservation practice of Chinese timber structures: no originality to be changed, or conserve as found. Journal of architectural conservation, 12, 7-26.

33 Buchanan, A.H. (2001), Structural design for fire safety. UK: John Wiley & Sons Ltd; 2001.

34 Kasal, B., Anthony, R. (2004). Advances in in situ evaluation of timber structures, Prog Struct Eng Mater, 6 (2):94–103

35 Gramatikov, K., Arangjelovski, T., Docevska, M. (2015). Assessment of damaged timber structures using proof load test-experience from case studies. Combined use of NDT/SDT methods for assessment of structural timber members. COST Action FP1101 - State of the art report, Machado J.S., Riggio M, Descamps T. (eds.): 223-227

36 Piazza. M., Riggio. M. (2008) Visual strength grading and NDT of timber in traditional structure, J. of Building Appraisal, 3:267–296.

37 Anthony. R.W., Dugan, K.D., Anthony, A. (2009). A grading protocol for structural lumber and timber in historic structures, Grant Number MT-2210-05-NC-05, National Center for Preservation Technology and Training, Natchitoches, LA.

38 Riggio. M., Anthony, R., Augelli, F., Kasal, B., Lechner, T., Muller, W., Tannert, T. (2014) In situ assessment of structural timber using non-destructive techniques. Materials and Structures. 47: 749-766

39 Dackermann, U., Crews, K., Kasal, B., Li, J., Riggio, M., Rinn, F., Tannert, T. (2014). In-situ assessment of structural timber using stress-wave measurements. Materials and Structures 47: 787–803

40 Ilharco, T., Lechner, T., Nowak, T. (2015). Assessment of timber floors by means of non-destructive testing methods. Constr. Build. Mater. 101 (2):1206–1214.

41 Tannert, T., Anthony, R.W., Kasal, B., Kloiber, M., Piazza, M., Riggio, M., Rinn, F., Widmann, R., Yamaguchi, N. (2014). In situ assessment of structural timber using semi-destructive techniques. Materials and Structures 47:767-785

42 Kloiber, M., Drdacky´, M., Machado, J.S., Piazza, M., Yamaguchi, N. (2015). Prediction of mechanical properties by means of semi-destructive methods: A review. Constr. Build. Mater. 101 (2): 215–1234.

43 Feio, A., Machado, J.S. (2015) In-situ assessment of timber structural members: Combining information from visual strength grading and NDT/SDT methods – A review. Constr. Build. Mater. 101 (2):1157–1165.

44 Sousa, H.S., Machado, J.S., Branco, J.M., Lourenço, P.B. (2015). Onsite assessment of structural timber members by means of hierarchical models and probabilistic methods, Construction and Building Materials 101 (2):1188–1196.

45 Sandak, J., Sandak, A., Riggio, M. (2015). Multivariate analysis of multi-sensor data for assessment of timber structures: Principles and applications, Construction and Building Materials, 101: 1172–1180.

46 UNI 11141, Cultural heritage - Wooden artefacts - Guidelines for wood dendrochronological dating. Ente Nazionale Italiano di Unificazione, 2004.

47 Piazza, M., Riggio, M. (2007). Typological and Structural Authenticity in Reconstruction: The Case of the Timber Roof of the "Pieve" in Cavalese, International Journal of Architectural Heritage, 2007, pages 60-81, Vol.1

48 SIA 269/5:2011 Existing structures – Timber Structures, Schweizer Norm, Swiss Society of Engineers and Architects, Zurich, Switzerland

49 Semplici, M. (2007). The Documentation of the Failures of the Timber Structures in the "Nominations Files" and in the "ICOMOS Evaluations", for the Inscription in the World Heritage List. From Material to Structure - Mechanical Behaviour and Failures of the Timber Structures. ICOMOS IWC - XVI International Symposium – Florence, Venice and Vicenza 11th -16th November 2007.

50 Tsakanika, E. (2015). Inscription in the UNESCO World Heritage List of the wooden Tserkvas of the Carpathian region in Poland and Ukraine. The field evaluation mission. Shatis'15 - 3rd International Conference on Structural Health Assessment of Timber Structures. Wroclaw, Poland, 9–11 September 2015.

51 ICOMOS, International Wood Committee: Principles for the Preservation of Historic Timber Buildings, 1999

52 ICOMOS, International Scientific Committee for the Analysis and Restoration of Structures of Architectural Heritage (ISCARSAH) Principles for the analysis, conservation and structural restoration of architectural heritage, 2003.

53 Larsen, K.E. (1992). A note on the authenticity of historic timber buildings with particular reference to Japan. In Proceedings of the 8th ICOMOS International Wood Committee (IIWCC), Kathmandu, Patan, and Bhaktapur, Nepal, November 23–25, 1992.

54 Larsen, K. E., and Marstein, N. (2000) Conservation of historic timber structures, Butterworth-Heinemann, Oxford, U.K.

55 Lemayre, R., Stovel, H., eds. (1994). The Nara document on authenticity, World Heritage Convention, Nara, Japan.

56 Canada Parks, 2010, Standards and Guidelines for the conservation of historic places in Canada. Canada's Historic Places. 2010.

57 ICOMOS IIWC, 2016 ,PRINCIPLES FOR THE CONSERVATION OF WOODEN BUILT HERITAGE, accessed on 27/05/2017 at http://iiwc.icomos.org/assets/1999-2016-principles-comparison-c.pdf

58 D'Ayala, D., Meslem, A., Vamvatsikos, D., Porter, K., Rossetto, T., Silva, V. (2015) Guidelines for Analytical Vulnerability Assessment of Low/Mid-Rise Buildings, Vulnerability Global Component Project. DOI 10.13117/GEM.VULN-MOD.TR2014.12

59 D'Ayala, D. (2013). Assessing the seismic vulnerability of masonry buildings. Handbook of Seismic Risk analysis and management of civil infrastructure systems (pp. 334-365). Woodhead publishing.

60 FEMA (2005), Hazus® -MH 1.1 Multi-hazard Loss Estimation Methodology, Washington DC

61 FEMA (2015), Hazus® -MH 2.1 Advanced Engineering Building Module Technical and User Manual, Washington DC

62 D'Ayala, D., Galasso, C., Putrino, V., Fanciullacci, D., Barucco, P., Fanciullacci, V., Bronzino, C., Zerrudo, E., Manalo, M., Fradiquela, C., Regalado, J. (2016), Assessment of the Multi-Hazard Vulnerability of Priority Cultural Heritage Structures in the Philippines, ICONHIC 2016, Chania, Crete

63 FEMA (2012), FEMA P-807: Seismic Evaluation and Retrofit of Multi-Unit Wood-Frame Buildings With Weak First Stories, Washington DC, May 2012

64 CEN EN 1995-1-1:2004. Eurocode 5, Design of timber structures, European Committee for Standardization

65 ISO 2394:2015. General principles on reliability for structures

66 Luechinger, P., Fischer J., (2015). New technical Rules for the Assessment and Retrofitting of Existing Structures. European Commission's Joint Research Centre (JRC). Report EUR 27128 EN

67 Česka Technická Norma, ČSN 73 0038:2014, Hodnocení a ověrováni existujících konstrukcí. Doplňující ustanovení (Assessment and verification of existing structures. Supplementary guidance – in Czech)

68 D.M. 14.01.2008, Nuove norme tecniche per le costruzioni, G.U. 04.02.2008, n. 29, Ministero delle Infrastrutture, dell'Interno e Dipartimento Protezione Civile, Roma (in Italian)

69 Diamantidis, D. (2001). Probabilistic Assessment of Existing Structures – A publication of The Joint Committee on Structural Safety (JCSS), RILEM Publications S.A.R.L

70 CEN EN 1998-3:2005, Eurocode 8: Design of structures for earthquake resistance – Part 3: Assessment and retrofitting of buildings, European Committee for Standardization.

71 Macchioni, N., Piazza, M. (2006). Italian Standardisation Activity in the Field of Diagnosis and Restoration of Ancient Timber Structures. In Structural Analysis of Historical Constructions SAHC 2006. New Delhi. P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.): 395-403

72 UNI 11161:2005. Cultural Heritage – Wooden Artefacts – Guideline for conservation, restoration and maintenance. UNI (Ente nazionale italiano di unificazione) (in Italian).

73 UNI 11119:2004. Cultural Heritage – Wooden Artefacts – Load Bearing Structures of buildings. Criteria for the preliminary evaluation, design and execution works. UNI (Ente nazionale italiano di unificazione) (in Italian).

74 UNI 11118: 2004. Cultural Heritage – Wooden Artefacts – Criteria for the Identification of the Wood Species. UNI (Ente nazionale italiano di unificazione) (in Italian).

75 CEN EN 335:2013. Durability of wood and wood-based products – Use classes: definitions, application to solid wood and wood-based products. European Committee for Standardization.

76 Mannucci, M., Brunetti, M., Macchioni, N. (2011) The Italian Standard UNI 111119:2004 for the in-situ diagnosis of timber structures: pros and cons after 5 years of practical application and proposals for emendations, SHATIS 2011 International Conference on Structural Health Assessment of TImber Structures, Lisbon, 16–17 June 2011.

77 Touza Váquez, M., Soilán Cañás, A., Lorenzo Fouz, D. (2013). Evaluation of the Load-Carrying Capacity in Bending of Large Cross Section “Pitch Pine” Beams in Standing Structures, Advanced Materials Research, Vol. 778, pp. 410-417, 2013

78 Sousa, H. S., Branco, J. M., Lourenço, P. B. (2013). Effectiveness and Subjectivity of Visual Inspection as a Method to Assess Bending Stiffness and Strength of Chestnut Elements, Advanced Materials Research, Vol. 778, pp. 175-182

79 American Society for Testing and Materials, Annual Book Standards, Vol. 04.10, D 245, Standard Practice for Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber; D 2555, Standard Test Methods for Establishing Clear Wood Strength Values, ASTM, West Conshohocken, PA. (2012)

80 Dietsch, P., Koehler, J. (eds) (2010). Assessment of Timber Structures, COST Action E55 “Modelling of the Performance of Timber Structures”, Shaker Verlag

81 Fassina, V. (2014). CEN TC 346 Conservation of Cultural Heritage-Update of the Activity After a height Year Period. Engineering Geology for Society and Territory - Volume 8 pp 37-41

82 Riggio, M., Macchioni, N. (2014). Assessment of historical timber structures: interaction of COST ACTION FP1101 with the CEN TC 346. Proceedings of the PROHITECH 2014 - 2nd International Conference On Protection Of Historical Constructions, 7-9 May 2014, Antalya, Turkey.

83 Parisi, M. A., Chesi, C., Tardini, C. (2013) Seismic vulnerability of timber roofs, Advanced Materials Research. 778:1088-1095.

84 Applied Technology Council, *ATC-20: Procedures for Postearthquake Safety Evaluation of Buildings*, revised, 2005.

85 Federal Emergency Management Agency, Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook, FEMAP-154, Third Edition, January 2015

86 Baggio, C., Bernardini, A., Colozza, R., Corazza, L., Della Bella, M., Di Pasquale, G., Dolce, M., Goretti, A., Martinelli, A., Orsini, G., Papa, F., Zuccaro, G. 2009, “Agibilità e danno nell’emergenza sismica. Manuale per la compilazione della scheda di 1° livello di rilevamento danno, pronto intervento e agibilità per edifici ordinari nell’emergenza post-sismica (AeDES)” Presidenza del Consiglio dei Ministri, Dipartimento della Protezione Civile, giugno 2009 (in Italian).

87 GU Serie Generale n.55 del 7-3-2006, (2006) Approvazione dei modelli per il rilevamento dei danni, a seguito di eventi calamitosi, ai beni appartenenti al patrimonio culturale. Scheda per il rilievo del danno ai beni culturali – Chiese, Modello A-DC, MiBAC (2006a) (in Italian).

88 GU Serie Generale n.55 del 7-3-2006, (2006) Approvazione dei modelli per il rilevamento dei danni, a seguito di eventi calamitosi, ai beni appartenenti al patrimonio culturale. Scheda per il rilievo del danno ai beni culturali – Scheda per il rilievo del danno ai beni culturali – Palazzi, modello B-DP, MiBAC (2006b) (in Italian).

89 Kelley, S.J., Sparks, S.P. (2010). ICOMOS Methodology for Building Assessment and Mitigation following the 2010 Haiti Earthquake. http://www.rdmuch.jp/en/project/itc/training_guide/sections/section_3/files/ICOMOS_Haiti_Methodology.pdf.

90 D'Ayala, D. F., Tsai, P. H. (2008). Seismic vulnerability of historic Dieh-Dou timber structures in Taiwan. Engineering Structures, 30 (8), 2101-2113. doi:10.1016/j.engstruct.2007.11.007

91 Tsai, P. H., D'Ayala, D. (2011). Performance-based seismic assessment method for Taiwanese historic Dieh-Dou timber structures. Earthquake Engineering and Structural Dynamics, 40 (7), 709-729. doi:10.1002/eqe.1050

92 Žnidarič ,A. (2013) e-bridge – Bridge Inspection Software, Technical Background, V0.5, Slovenian National Building And Civil Engineering Institute.

93 Pazlar, T., Kramar, M. (2014) Assessment of Timber Bridges in Slovenia. Proceedings of the COST Timber Bridge Conference - CTBC 2014. 25–26 September 2014. Bern University of Applied Sciences. Biel, Switzerland

94 Cacciotti, R., Blaško, M., Valach, J. (2014) A diagnostic ontological model for damages to historical constructions. Journal of Cultural Heritage

95 Novelli, V. I., & D'Ayala, D. (2014). LOG-IDEAH: LOGic trees for identification of damage due to earthquakes for architectural heritage. Bulletin of Earthquake Engineering, 1-24. doi:10.1007/s10518-014-9622-0

96 D'Ayala, D., & Speranza, E. (2003). Definition of Collapse Mechanisms and Seismic Vulnerability of Historic Masonry Buildings. Earthquake Spectra, 19 (3), 479-509. doi:10.1193/1.1599896

97 Frese, M., Blass, H.J. (2011) Statistics of damages to timber structures in Germany. Engineering Structures 33:2969-2977.

98 Toratti, T. (2011) Proposal for a failure assessment template. Engineering Structures 33:2958-2961

99 Frühwald Hansson, E. (2011) Analysis of structural failures in timber structures: Typical causes for failure and failure modes. Engineering Structures 33:2978-2982

100 Ross, P. (2002). Appraisal and repair of timber structures, Thomas Telford, London

101 Augelli, F. (2014) Wooden cultural heritage. Guidelines, standards and methods of representation, National University of Architecture & Construction of Armenia 2 (53):21-33

102 EN 844-10:1998. Round and sawn timber - Terminology - Part 10: Terms relating to stain and fungal attack. European Committee for Standardization.

Table 1. Comparison of Standard and guidelines

	Relevance N. National I. Intern.	Main objective	Scope of the assessment A. Protection/Document. B. Vulnerability/Damage C. Safety/Serviceability	Level of the investigation 1. Preliminary 2. General 3. Detailed	Timber	Other materials	Existing structures
FEMA 807:2012	N	Seismic evaluation and retrofit	B	1,3	X		X
ISO 13822:2010	I	Assessment of existing struct.	C	1, 3	X	X	X
ISO 2394:2015	I	Reliability of structures	C	2 , 3	X	X	X
Eurocode 5	I	Design of timber struct.	C	-	X	-	-
ČSN 730038:2014	N	Assessment of existing struct.	C	2 and 3	X	X	X
NTC 2008	N	Structural design	C	-	X	X	
SIA 269/5:2011	N	Assessment of existing struct.	C	1, 2 and 3	X		X
UNI 11138:2010	N	Intervention on timber struct.	C	2 and 3	X	-	X
UNI 11118:2004	N	Wood species identification	C	3	X	-	X

UNI 11119:2004	N	On-site inspection	C	3	X	-	X
EN 335:2013	I	Durability of wood and wood - based products. Use classes:.	B	2	X	-	X
ASTM D 245:2012	I	In-situ grading of structural timber	C	3	X	-	X
COST ACTION IE0601	I	Assessment of timber struct.	C	1, 2 and 3	X	-	X
COST E55	I	Assessment of timber element	C	3	X	-	X
ICOMOS-ISCARSAH	I	Assessment of existing struct.	A-C	1, 2 and 3	X	X	X
ICOMOS-IWC	I	Assessment of existing struct.	A-C	1, 2 and 3	X		X

Table 2. Synoptic table of official inspection tools for existing structures

Document name	**Issuing authority/ country**	**Structure /building type**	**Material**	**Type of vulnerabilit y/damage**	**Type of inspection**	**Type of form**
ASCE 41-13 Tier 1	ASCE/US	Modern	Any	Seismic	Pre and Post-event	Paper/pdf
ATC-20	ATC/US	Modern (including wood frame)	Any	Seismic	Post-event	Paper/pdf
FEMA 154	FEMA/US	Modern (including wood frame)	Any	Seismic	Post-event	Paper/pdf
AEDES	Italian National Department of Civil Protection/IT	Ordinary buildings	RC, steel, masonry	Seismic	Post-event	Paper/pdf
A-DC PCM-DPC MiBAC	Italian National Department of Civil Protection and MiBAC/IT	Churches	Masonry and timber	Seismic	Post-event	Paper/pdf

B-DP PCM-DPC MiBAC	Italian National Department of Civil Protection and MiBAC/IT	Palaces	Masonry and timber	Seismic	Post-event	Paper/pdf
Ebridge	Slovenia Roads Agency / SI	Bridges (modern and historical)	Any	Any	Periodical	Software/ digital database

Table 3. Assessment tools for timber structures – literature sources

Reference	**Structure type**	**Material**	**vulnerability /damage**	**Type of inspection**	**Type of form**
Parisi et al., 2013	Historic roofs	Timber	Seismic	Pre- and post-event	Paper/pdf
Toratti, 2011	Modern	Timber	Any	Post-event	Paper/pdf
D'Ayala et al 2016	Historic roofs, timber framed walls	Masonry and timber	Seismic and wind	Pre- and post-event	Electronic/ paper
D'Ayala Speranza 2003	Historic buildings	Masonry and timber roof and floors	Seismic	Pre- and post-event	Electronic/ paper
Caciotti et al.	Historic buildings	Masonry and timber	Any	Pre- and post-event	Electronic
Tampone 1996	Historic structures	Timber	Any	Pre- and post-event	Paper
Ross 2002	Historic structures	Timber	Any	Pre- and post-event	Paper
Augelli 2014	Historic structures	Timber	Any	Pre- and post-event	Paper