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Guidelines for On-Site Assessment of Historic Timber Structures

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In the scope of European Cooperation in Science and Technology–Wood Science for Conservation of Cultural Heritage (COST IE0601–WoodCultHer) (available at http://www.woodculther.org) it was agreed to produce Guidelines for the Assessment of Historic Timber Structures, covering the principles and possible approaches for the safety assessment of old timber structures of historical relevance that could be used as the basis for possible European Standards, as discussed with CEN/TC346 (Conservation of Cultural Heritage).

This approach was targeted at all those concerned with the conservation of heritage buildings. These guidelines should also help decision-making regarding the need for immediate safety measures. The aim is to guarantee that inspection and assessment measures provide the necessary data for historical analysis, structural safety assessment, and planning of intervention works, while having minimal impact on the building fabric (the original materials, structural systems, and techniques).This article provides information on the criteria to be used in the assessment of load-bearing timber structures in heritage buildings. It covers the preliminary assessment (desk survey, preliminary visual survey, measured survey, structural analysis, and preliminary report), as well as the detailed survey of timbers (with a special emphasis on visual strength grading on site) and carpentry joints. The subsequent diagnostic report and the detailed design of repairs are outside its scope.

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Keywords assessment, timber structures, historic, heritage, on-site, strength grading, carpentry joints

1. FOREWORD

This article originates from a document with the same name discussed within the Task Group "Assessment of Timber Structures" set within European Cooperation in Science and Technology–Wood Science for Conservation of Cultural Heritage (COST IE0601–WoodCultHer) (available at http://www.woodculther.org), which could be used as the basis for possible European Standards, as discussed with CEN/TC346 (Conservation of Cultural Heritage). This article is targeted at all those concerned with the conservation of heritage buildings and covers the principles and possible approaches for the safety assessment of old timber structures of historical relevance.

1.1. Scope and Field of Application

A distinction needs to be made between heritage/historic structures and other existing structures, even if many of the assessment methods are common to both. A greater value is placed on the fabric of heritage structures because of their historical significance. This value may justify greater expense both in the survey, diagnosis, and assessment of the structure and in the subsequent repair methods that might be employed. Repair or strengthening work should only be carried out for a heritage structure as a last resort and then any intervention should be kept to a minimum. The best possible assessment of its existing structural characteristics must be made, which might require the use of more precise and sophisticated methods than are used for other existing structures, with associated costs that could not otherwise be justified.

This document provides information on the criteria to be used in the assessment of load-bearing timber structures in heritage buildings. It is targeted at all those concerned with the conservation of heritage buildings that contain wooden elements, including the specialists employed and the building owners or authorities who are responsible for these buildings. This document should also help decision-making regarding the need for immediate safety measures. The aim is to guarantee that inspection and assessment measures provide the necessary data for historical analysis, structural safety assessment and planning of intervention works, while having minimal impact on the building fabric (the original materials, structural systems, and techniques).

Briefly, the steps required for the assessment of an historic timber structure and the planning and execution of any intervention are as follows (Figure 1):

1. A ***desk survey*** to deal with the history of the structure making clear its heritage value. This survey should also take into account the intentions of the building owner regarding its use and accepted alterations, so that the intended ultimate load and environmental conditions are clearly stated.
2. A ***preliminary visual survey*** simply to obtain an overview of the structure that is sufficient to plan the next stage, identifying what provisions need to be made to gain safe access to the timber structure.

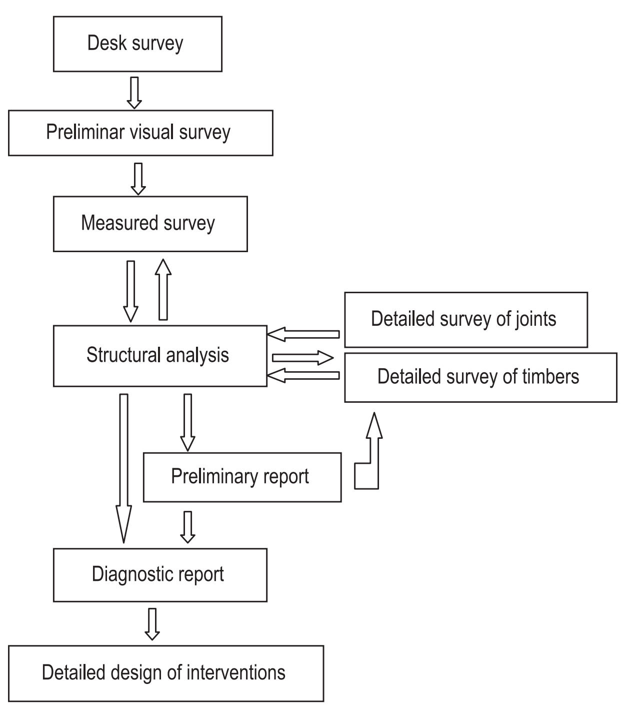

FIG. 1. Steps required for the assessment and planning of interventions in historic timber structures.

3. A ***measured survey*** to determine the overall disposition of the structural members and locate the main problems. This survey should include principal dimensions and the nominal sizes of all members. It should also note any obvious signs of damage, decay, or structural distress, which will need to be investigated in more detail at a subsequent stage.
4. A ***structural analysis*** to determine the overall forces and general levels of stress within the structure.
5. A ***preliminary report*** to specify any additional survey work that may be necessary. (One might need to do this simply to provide the client with a more accurate estimate of costs.) This report will indicate what aspects of the structure require further investigation and what methods are recommended. It will draw upon the four tasks already carried out, identify the aspects of the structure that need to be preserved for their heritage value, identify areas of high stress and/or significant biological attack that need further measurement, and note any "defects" within the structure and identify the vulnerable areas.

These items are dealt with in detail in Part I of this article.

6. A ***detailed survey*** as indicated in the preliminary report. This survey will include the measurement of areas of biological attack and damage, the assessment of timber grades, and the results of non-destructive methods where appropriate, and will also consider the adequacy of joints. This survey is dealt with in detail in Parts II and III of this article.
7. A ***diagnostic report*** on the condition of the structure and causes of distress with proposals for remedial measures where necessary. This report may imply a new structural analysis considering the data gathered in the detailed survey.
8. A ***detailed design of repairs*** and maintenance in collaboration with other members of the team. Whenever possible, the carpenters/contractors should be included in this discussion. However, it is recognized that this design is often impossible under public contracts and public tendering processes, meaning that future adjustments may be necessary for the execution of works and final preparation of execution drawings.

Proposals for remedial measures need to take into account the owner's intentions as indicated in Item 1, but also to point out any areas of conflict between: a) the need to preserve its heritage value, b) the owner's intentions, and c) the need for public safety. Although the list suggests a linear process, it is essential to recognize that conservation frequently involves iterations. For example, the preliminary visual survey might raise questions that could be answered by a more thorough desk survey, able to document changes that have been observed in the structure. Iterations between structural analysis and repair strategy stages are also often required. A holistic approach is always required, considering and assessing the structure as a whole, rather than just the individual members and joints.

2. PART I: PRELIMINARY ASSESSMENT

2.1. Part I: Introduction

2.1.1. Need for assessment

One would normally assume that a structure that has proved to be adequate in the past will continue to be structurally adequate requiring no detailed assessment of timber strengths, although due consideration might still be needed regarding extreme events such as hurricanes, snow storms, earthquakes, fires or other.

However, a structural assessment is certainly needed in cases of:

1. A change in use of the structure and hence a possible change in loads.
2. Significant decay or insect damage to the timbers, or damage suffered by the structure (e.g., due to fire).
3. Mechanical damage or excessive deflection indicating overloading of the timbers in the past, inferior initial design, or poor quality of the used materials.
4. Alterations/interventions to the structure during its lifetime that have resulted in a reduction of its strength or changes to the original structural system.

It should be mentioned that there are occasional examples of poor initial design or workmanship. In such situations, or whenever past structural alterations or damage of timber and joints imply insufficient strength, measures must be taken to guarantee an adequate safety level and/or to limit public access.

2.1.2. Principles

Within the scope of these guidelines, the assessment of any existing timber structure has to be performed by desk work (e.g., historic/architectural survey, structural analysis), on-site inspections and other complementary on site measurements and laboratory tests. The general principle is that all inspections and surveys are non-destructive so that no part of the structure has to be removed or sampled except for small samples used for identification of timber species and biological decay agents. In any case the sampling should not modify the mechanical properties of the elements or have an impact on the other properties (e.g., aesthetical or historical) of the timber structure.

2.1.3. Time-dependent results

Note that the assessment results pertain to the moment of assessment since degradation is generally a continuing process and further deterioration must be anticipated until suitable remedial measures have been adopted and become effective. This situation occurs in the presence of an active insect attack requiring intervention that may or may not have immediate results, or when high moisture content levels not only require solving the water intake source but also subsequent drying of timber and adjacent building materials before biological degradation can be curtailed.

2.1.4. Necessary conditions for the inspection

The following conditions must be met (UNI 11119):

- *Safety*: The timber structure must provide reasonable safety level to walk on or walk under, otherwise propping or shoring is necessary.
- *Accessibility*: The timber members must be made sufficiently accessible to allow for the assessment procedures to be carried out. Access will depend upon the nature of the structure itself and may be as basic as simple ladder or may require full scaffolding. Accessibility has a great influence on the choice of the inspection technique.
- *Lighting*: Proper light (quality and intensity) must be used to permit a correct visual examination of the joints, the timber members as a whole, and the wood surface details. Note that some control over the lighting may be necessary since surface features are sometimes easier to see with appropriate directional lighting rather than bright general light.
- *Cleaning*: The surface of the wood must not be covered or concealed in any way by debris, dirt, and dust. The surveyor must be adequately equipped to clean areas of the timbers as required by using dry processes (e.g., brushing, vacuum cleaning, air pressure).

Also of note:

- Note 1: In the case of decorated (painted) or covered timber members, wood surface accessibility and visibility may not be fully possible. In such cases, the inspection report must detail what information was not obtained and explain why.
- Note 2: Inspection is particularly important in highly stressed points of the structure, particularly areas subjected to high bending moments, near joints and at the supports. In all parts of the structure where a regular visual inspection is not possible, such as the ends of beams inserted into supporting walls, alternative inspection methods (e.g., by resistance drilling methods), or indirect assessment techniques should be carefully planned.

2.2. Part I: Desk Survey—Historical Research and Analysis

A desk survey is an integral part of any conservation process. Its purpose is to gather documents and other sources of information (e.g., drawings, photos, oral testimonies) relating to the structure, which will provide information on the historical aspects of the structure and any which relate to its present use and status as a heritage building. Any information regarding the loading conditions during its lifetime, previous interventions or restorations should be included.

In cases for which the structure is mainly of timber, a timber structures specialist might well be taking the lead and so be responsible for the desk survey. In such cases it is important that the timber structures specialist is conversant with the history of the structural type and the possible location of historic documents.

2.3. Part I: Preliminary Visual Survey

A preliminary visual inspection is required to identify any obvious damage and susceptible zones of the structure, to determine the assessment strategy, and to identify the possible need for any immediate propping or stabilizing measures, and/or restriction of access (Figure 2). A specialist who understands timber structures should do this work.

The inspection should begin by looking at where problems are most likely to occur. This preliminary survey is also required to evaluate the working conditions (accessibility, lighting, and cleaning) and the safety conditions for the operators and related safety measures (e.g., to identify and circumscribe inaccessible areas because of risks of structural collapse, risk of falling).

2.4. Part I: Measured Survey

This stage is the foundation for all that follows and must be carefully carried out and documented so that other members of the conservation/restoration team can draw it upon. It must comprise geometrical, diagnostic and technological aspects.

2.4.1. Geometrical survey

This survey should comprise:

- A drawn survey of the structure, fully dimensioned (this survey should also include non-structural members and note possible interactions with other structures). In some cases the usual two-dimensional drawings have to be completed by three-dimensional axonometric sketches and drawings of construction details (Figures 3, 4, and 5).

FIG. 2. Need for propping.

- The typical dimensions and shape (when necessary) of all timbers.
- A note of the method of conversion identifying sawn faces and axe hewn or adzed faces.
- A note of joint types, materials and typical dimensions where these could be clearly seen.
- Where it is the timber structure that is of historic significance (such as in medieval timber framed buildings) the survey should in addition include a dimensioned drawing of all significant structural timbers, noting features such as tool marks and marks made by the carpenters in setting out the framing.

2.4.2. Technological survey

This survey should comprise:

- *Identification of wood species*: Initially this identification may be conducted through a quick visual inspection, at least placing the timbers within a clear group, if only to distinguish between softwood and hardwood. A note should also be made of a possible mix of species, often differences in the primary and secondary members.
- *Determination of wood moisture content*: Initially measurements are taken only in specific locations of the structure, where the local conditions suggest the presence of higher moisture content. However, measurements must also be taken in other locations to determine the general equilibrium moisture content of the timber at the time of the inspection.
- *Determination of environmental conditions*: Service Classes defined by EN 1995-1-1 (relevant for mechanical properties) and Use Classes defined in EN 335-2 (related to biological hazard) to which the timber member is exposed must be identified.[1] Note that different parts or members of a timber structure may belong to different hazard classes. If differences between transitory (previous to or during a possible intervention) and target (final) conditions are important, both situations must be identified.
- *Dendrochronology*: This study may be carried out to provide additional information on provenance and dating and should be undertaken if the dating of the structure is in doubt and there are adequate large databases for the species and region considered or reliable possibility of dating by using the reference from the same area but coming from different species (*heteroconnection*), or by using the references from the same species but coming from different regions (*teleconnection*).

[1]Service Classes 1 and 2 fit into Use Classes 1 and 2, respectively. Service Class 3 includes Use Classes 3, 4 and 5.

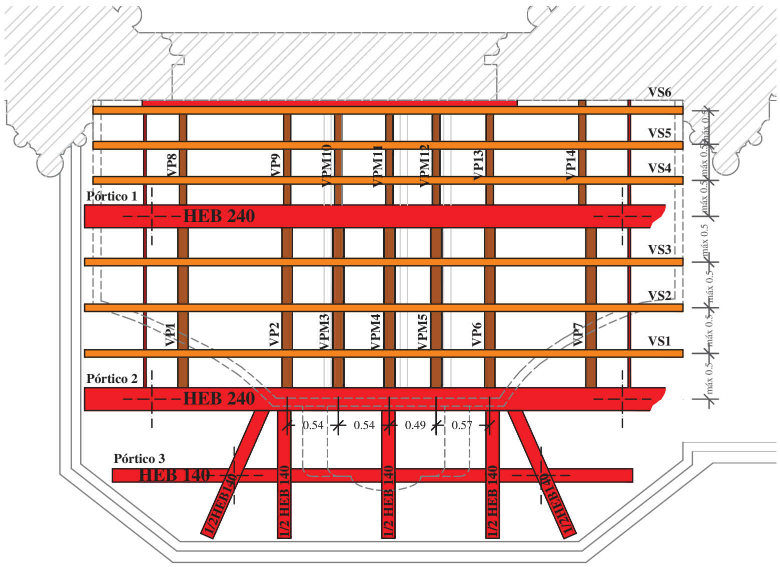

FIG. 3. Dimensioned survey of a timber floor. VP, PM: main beams; VS: secondary beam (dimensions in meters).

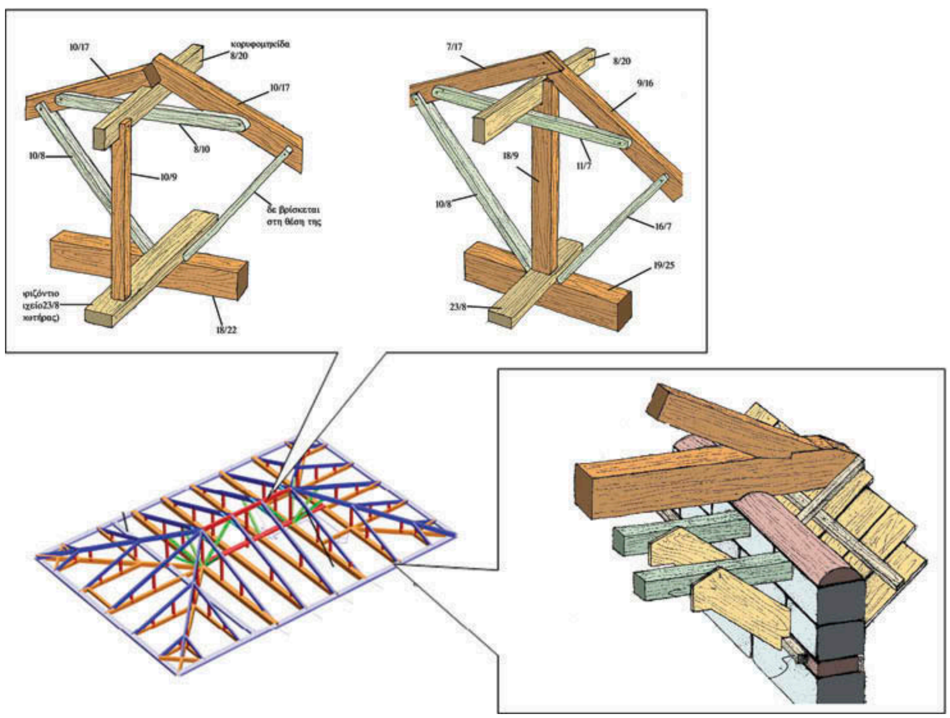

FIG. 4. Hagi Mehmet Aga mosque (Rhodes, Greece). Examples of axonometric drawings: general lay-out of the structural system and construction details.

2.4.3. Defects and damage survey

This survey should comprise records of:

- Any areas of biological or fire damage (type/causing agent, location, and extension).
- Type, location, and extension of main defects of timber members (specially knots and slope of grain). Since the effect of these defects is reduced considerably when they occur in association with wane, this occurrence must also be reported; since drying fissures follow the grain direction, these hardly affect the load-carrying capacity when they are parallel to the beam/column axis. However, drying fissures can be decisive when deviating from this direction. Consequently, when applicable, a fissures pattern drawing must be made.
- Location of critical areas due to biological attack or damage.

FIG. 5. Spatial structure of high complexity.

- Any areas of mechanical damage or structural distress in the timbers, such as timber cracks (due to overloading), structural failure of members and joints or excessive deflections (Figure 6).
- A note of any distress in supporting structures or members (e.g., masonry structures, foundations) and in non load-bearing timber elements that interact with the timber structures.
- Any timbers missing from the structure (possibly indicated by empty mortises).
- A note of any indications of changes made to the structure during its life (Figure 7). These changes might have been made to accommodate changes in the plan or external form of the building or previous repairs. These changes often result in changes to the load paths and, consequently, in changed loading at members and connections. When known, these changes must be reported.
- Any places where timbers could not be clearly seen and where opening of the structure might be required. Examples are wall plates concealed by roof coverings, timbers behind plasterwork or timber beams built into masonry walls.

FIG. 6. Timber failure in the vicinity of the joint.

FIG. 7. Missing part of the structure due to previous interventions.

2.5. Part I: Structural Analysis

The purpose of the structural analysis is to identify highly stressed areas of the structure where more attention is required during the survey. Thus it should identify the critical areas/zones that need special attention and possibly further inspection. It should describe the overall structural system and, where appropriate, determine the stress levels within the structure.

In some cases, a simple and conservative assessment of the structural scheme, of the member properties and their effective cross-sections, as well as joint performance, may be sufficient. Alternatively, the preliminary assessment might indicate the need for a more detailed analysis. In the case of spatial load-bearing systems, numerical analysis with 3-dimensional models may be necessary (Figure 8).

The structural analysis of an historic structure is a difficult process with many uncertainties because it is not always possible to estimate the strength and stiffness of structural members and joints, the load history, or the boundary conditions. Neither can one be certain whether elements of the fabric, which were not intended to be structural, may nevertheless be carrying load. A common mistake in numerical analysis is to assume that the joints are capable of transferring forces, which they cannot in fact. It may also be necessary to allow for members that

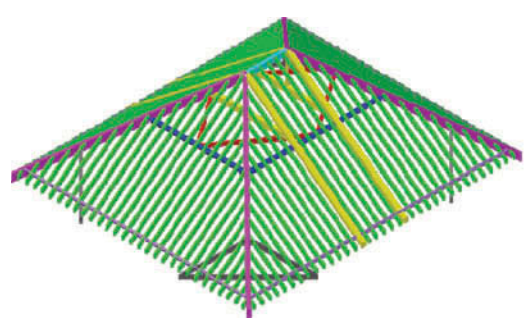

FIG. 8. Three-dimensional model of the timber roof structure.

have become sufficiently decayed that they have shed significant loads to other members. Therefore one may well have to consider more than one load path, possibly reviewing the structure itself to choose between them.

In contrast, if the mechanical properties of members can be assessed, they frequently exceed the so-called characteristic values that would be used in the design of new structures. That exceedance is because the 5% exclusion figure, which is used to define the characteristic values, is relatively low compared with the average for the material. Furthermore, when the mechanical properties are assessed successfully, there is need for a partial material factor $\gamma_M > 1{,}0$. If there is a change of use or some other modification that affects the levels of stress in the members, the analysis should consider the appropriate loads for those changes.

Historic timber structures have generally been more flexible that those designed today but have, nevertheless, performed satisfactorily. It is not, therefore, appropriate to apply modern service limit states, which might result in condemning perfectly adequate structures. The engineer should assess the overall stability of the structure as well as the behavior of individual members or individual frames. Therefore the adequacy of braces needs to be considered as well as that of the principal structural members. Some carpentry joints may be able to transfer moments to some extent, as well as shear and compression loads. Providing that suitable data is available for their moment-rotation capacity, their contribution to the overall structural performance may be taken into account instead of assuming them to be pinned joints.

2.6. Part I: Preliminary Report

This report should include:

- Dimensioned drawings of the structure completed with technical notes describing the structural system, and its principal features;
- Record of problems and pathology, as listed in clause I.4.;
- A note of any timbers and joints that have not been inspected and why;
- Structural calculations showing the loads on the structure and the stresses and deformations;
- Identification of the different structural member types – according to the type and level of stresses (described in Part II) and the location of critical areas –either from the point of view of the level of stresses or due to the presence of timber defects or biological damage;
- Service classes and classes;
- Interpretation of the causes of damage and general behavior of the structure (diagnosis); identification of additional survey and assessment work required, fully justifying the need for any recommended work and noting any places where the structure needs to be opened up to enable the survey work to be carried out; and
- Identification and justification of any specialist equipment that will be required.

3. PART II: DETAILED SURVEY OF TIMBERS

3.1. Part II: Introduction

The aim of the detailed survey is to obtain for the timber elements that are specified in the assessment report the following additional information (UNI 1119):

- Wood species;
- Moisture content values;
- Strength grade or strength values to be used in the structural analyses. Since strength grades, listed in standards (e.g., for new designed structures, the strength grades according to EN 338 are used) only provide characteristic values, assessment of the existing structural members into a strength class most probably result in a (very) conservative assessment;
- Characterization of biological damage.

These points are particularly important for all critical areas of the structure that have been identified and will enable stress levels to be recalculated to support the final diagnostic report that follows.

3.2. Part II: Identification of Wood Species

This identification may be conducted through visual inspection (as noted in Part I). In some cases, small samples for laboratorial identification of wood species (by microscopic analysis) may be required. The method used should be clearly stated.

Even where historic records provide information on wood species, these should be confirmed.

3.3. Part II: Determination of Wood Moisture Content and Moisture Gradients

The measurements should be taken for each element that has a higher risk of biological attack, such as close to the wall supports of floor beams and at roof edges and corners. In the presence of fungal attack or subterranean termite infestation,[2] which are closely related to high moisture content of timber, moisture content readings should be taken at several distances from the ends of the element. Measurements should be taken at various depths from the surface of the element by means of appropriate non-destructive methods such as insulated electrodes. The equipment used for that purpose must be calibrated for the specific species or group of species and readings be taken

[2]Some wood boring beetles such as *Xestobium rufovillosum* also prefer wet wood.

and corrected for the environmental conditions, according to the equipment manufacturer's specifications.

Moisture content measurements will help to determine the local environmental conditions and the biological risk level for each element. This could vary along the same element according to the local environments. This data will also help establish the potential for further progress of biological deterioration and to plan subsequent interventions aimed at reducing the risk.

3.4. Part II: Strength Grading of Timber

3.4.1. Principles

Relevant members in critical areas (see Definitions) must be strength graded, or the relevant actual strength properties assessed. This can be based on visual inspection of timber features and defects (visual grading), on non-destructive measurements of one or more physical or mechanical properties, or on an appropriate combination of both methods (UNI 1119:2004).

The ratio between applied stresses and the strength capacity of the timber member (stress level) for the mechanical properties corresponding to the timber quality that is representative of the structure and the effective (residual) cross-section representative of most members should be calculated. For the critical cross-sections (areas with high stress levels or higher degradation), the stress levels should be recalculated for the effective cross-section and the actual timber grade.

3.4.2. Basis of the strength grading of historic timbers and research needed

The intention behind any assessment of strength should be the retention of the maximum amount of historic material. Therefore the first task in assessing historic timbers is to consider their load conditions and to make some assessment of the magnitude of stresses they may be subjected to. This means that the first step is the recognition of the structural system and the use of appropriate structural models. Note that this may be an iterative process. Should one or more timbers prove inadequate for a proposed structural scheme, then an alternative load path may need to be considered.

The commercial grading of timbers into strength classes is carried out to obtain the maximum yield and for simplicity of specification by engineers. It takes no account of the conditions of use. In contrast, the location and stress conditions of historic timbers are known as are the positions of specific growth characteristics, thus allowing the importance of defects to be evaluated in relation to the applied stresses. As a simple example there is little point in grading a strut, which will only be loaded in compression, for characteristics that can only affect the ability of a member to resist bending. Moreover, in members subjected to bending, the size allowance for knots should vary depending on their particular position along the section and along the length of the element.

Current grading rules used for new timber structures are not well suited to historic timbers for a number of reasons.

- In current visual grading standards, *grades* refer to specific commercial timber sizes, which differ from the typical traditional scantlings and do not properly take into account size effect in old timber (dimensions and conversion process);
- Current grading rules make no allowance for the sizes of timbers and methods of conversion which were quite different in the past from current methods;
- The reliability of visual grading rules applied to old timber material and to many species used in the past has not been adequately assessed;
- Rules for commercial timber set limits on a number of singularities that are not grade-determining (e.g., distortion), they do not reflect the exact mechanical effect of fissures—that may be quite large in old structures—and are difficult to apply on site when just one or two faces and no ends can be made accessible;
- Most methods of visual grading derive fifth percentile values of mechanical properties, which may underestimate the true strength of specific beams; and
- The existing EN 338 strength classes system has not been devised with historic buildings in mind, where smaller steps between consecutive strength classes and even modified "strength profiles" would be more appropriate.

In spite of these difficulties there is no other guidance until further research has been carried out. Nevertheless, graders should be aware of the limitations listed above.

3.4.3. Identification of structural member types

Structural timbers may be divided into the following types:

1. Members subject to bending in conditions with no load-sharing, such as principal beams in floors and purlins in roofs.
2. Members subject to bending where load-sharing is possible, such as joists, and common rafters.
3. Members subject to direct compression, meaning struts or posts under axial load only.
4. Members in direct compression and bending, such as posts subject to wind loads or posts in frames where braces impose bending loads on posts.
5. Members in tension, such as king posts in roof trusses.
6. Members in tension and bending, such as tie beams of roofs that are also in bending from struts or principal rafters, or carry heavy ceiling loads.

Of note, Types 1 and 2 require the same approach to strength assessment.

The most important defects to take into account in grading are knots and slope of grain. Knot clusters in beams have a more severe effect towards areas of high bending moments, while splits and slope of grain are more significant towards the supports where shear forces are highest. Margin knots are the more critical and have a more severe effect on the tension side of a beam. Knots on the compression side are far less significant. However, as stated previously, the negative effect of knots and slope of grain is less pronounced when in combination with wane (where no fibers are cut through by a manufacturing process).

In cases of load-sharing, an increase of 10%, as indicated in Eurocode 5 (EN 1995-1-1) should be allowed to the strength of timber members.[3] However in historic buildings it may also be appropriate to allow a member to shed all or part of its load onto adjacent members. This allowance enables a single poor quality or severely damaged member to be retained as long as the adjacent members can carry the additional loads.

The deflection limits specified in modern design codes may not be appropriate for the historic building since, for example, some historic roof structures have a satisfactory performance in spite of large permanent deflections.[4] Moreover, floor structures are seldom required to carry a permanent loading that is close to the modern design requirements.[5] These are situations where the requirements of the specific client or public authorities need to be taken into account.[6]

Type 3 members do not generally require grading. Where compression members are large, as in the main posts of timber frames, stresses will be low and the effect of knots will usually be small. Where compression members are small, as in stud walls, knots may well have a serious effect on the stiffness of a member. However, as such structures are load-sharing systems it may be acceptable for the load on one stud to be shed to adjacent studs. Only when two or more adjacent studs have significant knots need any consideration be given to their grading.

Type 4 members generally require an assessment for strength in the vicinity of the brace/maximum moment. Allowance needs to be made for the reduction in section produced by the joint for example of a brace which is likely to be the most critical factor affecting the member load-bearing capacity. Assuming pin-ended members the bending moments will reduce to zero at the ends of the member and the assessment of strength should take account of the consequent reduction in stress along the length of the member.

Type 5 members are generally subject to low-tension stresses and will only be critical in area of joints. In this case, fissures are not important for the strength grading of the member, unless they are associated with high slope of grain, even if they are through the full width of the timber.

For Type 6 members, while the tension stresses are generally low, maximum bending moments may occur close to the ends so that the relaxation in the criteria for knots which applies to beams is not appropriate for these members. Note also that bending and shear forces may well be high at the same position in the member. Finally, in Types 5 and 6 members, allowance needs to be made for the reduction in section produced by the joint.

3.5. Part II: On-Site Visual Strength Grading of Structural Timber Members

According to the nature, dimension and position of defects, relevant timber element can be visually graded in order to obtain characteristic strength values. In the absence of the actual strength values for each timber member, it is necessary to obtain characteristic strength values for the timbers so that the structure itself can be assessed according to the principles of EN 1995-1-1. Some countries may have available visual grading rules for establishing the characteristic stresses for the commonly used species. However other countries may not have visual grading rules and corresponding strength data.

Should this lack of data be the case, in the absence of better judgment and bearing in mind that this may be a conservative approach, a method is needed to enable the timber specialist to place the timbers within the strength classes listed in EN 338. The method by which this can be done is to use the grading rules used elsewhere for equivalent timbers. The judgment on equivalence may be based first on species and then on density and modulus of elasticity. Only the grade-determining parameters should be taken into account (disregarding for this purpose the grade limits for distortion, resin pockets, bark, wane and biological attack) and careful judgment is required on the influence of fissures and knots according to the type of member as discussed in Section 3.4.3.

Guidance on the assignment of species, source and visual grades to the strength classes is given in EN 1912. Information on existing grading standards and the species to which they are normally applied is also given in this standard. In this context in order to assign a grade, it is necessary that all relevant strength determining growth characteristics and/or defects fall within the specified limits for that grade. The assignment of intermediate grades may be made at the engineer's discretion when adequately justified. For this purpose, only strength determining

[3] As noted in EN 1995-1-1, section 6.6, when several equally spaced similar members, components or assemblies are laterally connected by a continuous load-distribution system capable of transferring the loads from one member to the neighboring ones (e.g., planks), the member strength properties may be multiplied by the system strength factor $k_{sys} = 1.1$.

[4] This high deflection is usually the result of creep because the timbers were loaded while green, the adopted sections are insufficient to comply with modern serviceability limit conditions, and/or high moisture was present in the structure at a given time in the past. In addition, lower deflection limits set for modern timber building structures are mainly meant to avoid damaging brittle linings and facades, for the sake of the occupants' comfort and for aesthetics.

[5] An example is given in *Floor loads and historic buildings*, English Heritage (1992), which suggests lower office floor loadings than those in the present design code.

[6] In several cases, the loads deriving from the new use of the historic building have to be reconsidered because they may lead to excessive reinforcements, or even replacement of the original timber structural system.

features and defects should be considered for the purpose of assigning a grade to the timber member. Knots, slope of grain and density (or rate of growth) are certainly to be considered, whereas distortion may be ignored in all cases.[7] Fissures, wane and biological attack are to be taken into account elsewhere, but do not have to conform to the limits set for visual grades. Visual grading needs experienced conservators, or properly trained specialists.

The following principles apply (UNI 11119: 2004):

- Grade the entire member and, if necessary, identify each critical zone separately;
- If the number of visible sides of the timber member is less than three or if none of the end faces can be observed, this must be explicitly mentioned in the inspection report;
- If some areas are affected by mechanical damage or localized biological attack (fungal or surface insect attack) make it clear that the classification only applies to the undamaged section; and
- If some areas are affected by wood boring insect attack that has spread throughout the whole cross-section (widespread attack), then one should consider the whole cross-section when grading. Possible density loss may have to be considered.

3.6. Part II: Strength Assessment Using Non-Destructive Techniques

In some cases, on site visual inspection can be completed by supplementary tests through the use of one or more non-destructive methods with the aim of determining physical and/or mechanical properties, which can be clearly correlated with the strength of the critical section itself. Non-destructive tests may also be used to assess globally the structure (e.g. proof-loading, dynamic response).

Whichever methods are used, the tests must have the least possible impact, taking into account the characteristics and historical value of the structure and of the specific timber member under analysis. Given the uncertainty of the data obtained, when non-destructive testing methods are used, it is always necessary to check the measurements obtained against those obtained by different methods. Whenever possible, in using values supplied by such investigations, one shall consider the margins of error within the data.

[7]Engineers in charge of the structural analysis must pay special attention to the fact that modern standards (e.g., EN 1995-1-9) set limits on the deviation form straightness and, when elements exceed those limits require some correction of the equations used to verify stability limits, i.e. "bending stresses due to initial curvature . . . shall be taken into account", and a second order analysis shall be done. This point is particularly significant when dealing with members subject to direct compression and members in direct compression and bending.

3.7. Part II: Characterization of Biological Damage

3.7.1. Identification of biological damage

One shall recognize, specify and characterize biological damage (Figures 9 and 10). Possible correlation between this and environmental conditions must be analyzed.

Therefore, particular attention must be given to the analysis of moisture conditions in the vicinity of the wooden member or a part of it (for example, the ends of beams and trusses inserted in walls).

3.7.2. Assessment of effective cross-section

In the presence of fungal attack, the estimation of an effective cross-section, which may vary along the length of the element, is normally difficult. Non-destructive techniques (e.g., drilling methods) may be used to help establish the mass loss or density loss caused by fungal attack and the effective reduction of timber mechanical properties. The method used must be recorded. Where decay has penetrated the full cross-section

FIG. 9. Evidence of subterranean termites attack.

FIG. 10. Evidence of fungal attack.

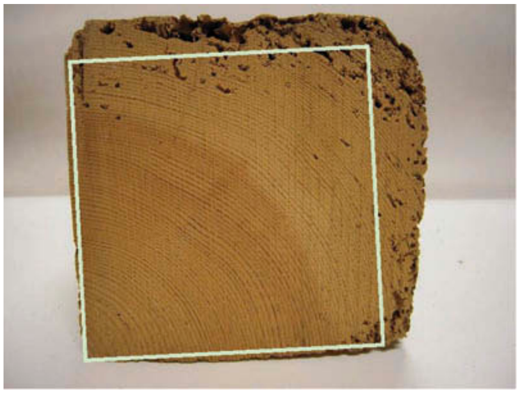

FIG. 11. Possible idealization of residual cross-section ("equivalent" sound cross-section).

the load-bearing capacity must be considered to be zero. Less severe situations of decay must be carefully judged and justified.

In the case of subterranean termites, the timbers may exhibit no external signs of attack, even if the element may have important internal degradation. The volume of material destroyed must be carefully estimated (e.g., by drilling or other non-destructive methods) in order to judge the corresponding strength loss and needed intervention. Where insect attack is confined to a well-defined area of the cross-section (normally the sapwood of a durable species), the effective (residual) cross-section should be reported and used to calculate the load-bearing capacity of the timber member (Figure 11).

3.7.3. Assessment of residual density (or equivalent density loss)

Where insect attack is in a diffuse pattern throughout the section the total cross-section could be used with the strength reduced to account for the reduction in average density, if applicable. An estimation of actual density or an estimation of loss of cross-section area should therefore be made.

4. PART III: DETAILED SURVEY OF TIMBER JOINTS

4.1. Part III: Introduction

It is important to understand the behavior of joints and the way in which they transfer loads. Some traditions of carpentry rely heavily on pegged mortise and tenon joints while other traditions use lap joints. Still others use nailed or bolted joints.

Historic joints may usually be considered as adequate for the loads that they are carrying and will require no detailed assessment except where there has been an increase in the load or when they show obvious deficiencies or damage. In such cases the stress conditions will depend upon details of the carpentry and close examination of the joints, possibly by drilling, might be required to determine the geometry of the joint and thus which parts are under stress. Note also that the stresses in either the foundation member or the joining member can be critical.

It is important to understand the way in which the joints were made (or should have been made) and the way in which they were intended to perform. The joints may not be performing in that way today because of poor workmanship in the first instance, because of changes that have occurred over time, or because of a combination of the above. Note that joints intended to work in one mode may have been subject to loads and stresses that they were not intended to carry. For example, a joint originally intended to transmit compression loads only may be called upon to carry bending moments as well. Thus, the actual load conditions of joints should, as far as possible, be considered when assessing their load-bearing capacity.

Common conditions to be considered are:

- Compression across the grain where the joining member bears on the foundation member. One or both of the members may be loaded across the grain.
- Compression at an angle to the grain in mortise and tenon joints. The critical condition is normally compression on the end of the tenon.
- Shear along the grain. This may be critical where there is short grain towards the end of a member in tension, e.g. behind the mortise or notch which is receiving thrust from a principal rafter at the end of a tie beam.
- Tension across the grain due to fasteners in line restraining timber shrinkage or due to poor joint design and detailing either related to geometry or small end distances.

Where joints are pegged, no allowance should be made for the capacity of the peg, because its stress condition cannot readily be determined. Therefore pegged mortise and tenon joints can only be considered as acting in compression. In pegged lap-dovetail joints it is the bearing of the dovetail that will be carrying any loads in tension. In several cases pegs or metal fasteners were not used for transferring loads but keep the timber parts connected.

4.2. Part III: Detailed Geometry

The timber specialist should be familiar with the types of joints used in the structure being assessed. The detailed geometry of critical joints should be measured, namely:

- Timber cross-sections;
- Details of the carpentry;
- Diameter and type of metal or wooden fasteners; and
- Edge and end distances.

Non-destructive methods (e.g., drilling resistance) may be used for the determination of hidden geometrical characteristics of joints (e.g., presence and dimensions of tenons and mortises, gaps).

4.3. Part III: Pathology

Workmanship needs to be considered in respect of:

- Poor fitting of the timbers;
- Insufficient spacing or end and edge distances of mechanical fasteners;
- Missing fasteners;
- insufficient bearing of beams; and
- Eccentricity of loading.

Changes over time may be:

- Corrosion of metal fasteners, straps and plates
- Shrinkage of timbers and associated fissures
- Biological attack
- Fire attack
- Intentional modifications (human interventions)
- Failures, movements (Figure 12), deformations as a result of excessive loading
- Crushing of timbers
- Buckling of metal fasteners

All such features need to be recorded.

4.4. Part III: Timber Quality and Conditions

In many cases the condition of timber at the joints, and hence the capacity of the joint to transmit load, may well be the principal factor determining the forces within a member. The density of the timber is the relevant mechanical property in determining the load-carrying capacity of the joint. Non-destructive techniques, e.g. resistance drilling may be a useful tool to obtain information on the density of the timber needed for calculations as well as to clarify the details of construction (existence and geometry of mortises or hidden parts of the joint).

Knots will only decrease the joint strength if they prevent proper insertion of fasteners. However, fissures in the jointing area may seriously affect its load-bearing capacity. Similarly, biological attack of timber at joints is particularly serious since even a surface degradation may have a great impact on the joint performance. Note that shrinkage of timbers may not only have affected the nature of the joint and its ability to carry load but in some cases may also have changed the overall behavior of the structure.

FIG. 12. Lack of contact and failure of the joint.

5. FINAL REMARKS

This article provides information on the criteria to be used in the assessment of load-bearing timber structures in heritage buildings. It covers the preliminary assessment (desk survey, preliminary visual survey, measured survey, structural analysis and preliminary report), as well as the detailed survey of timbers (with a special emphasis on visual strength grading on site) and carpentry joints. The subsequent diagnostic report and the detailed design of repairs, which are also fundamental tools for a safe, sound and respectful intervention, are however outside its scope.

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APPENDIX: DEFINITIONS

- ***Alteration*****:** Any kind of modification to wood (biological, mechanical, chemical) or to metallic materials occurring after their installation.
- ***Action*****:** Any agent (e.g., forces, deformations) that directly or indirectly produces stresses and/or strains for a building structure and any phenomenon (e.g., chemical, biological) that affects the materials that compose the building.
- ***Critical area/zone*****:** A part of a timber element with a length >150 mm, or equal to the depth of the member, whichever is the greater, which is considered to be relevant to the performance of the structure because of defects, position, and state of preservation and also stress conditions as determined by static analysis (UNI 11119: 2004).
- ***Critical cross-section*****:** The cross-section that is representative of a critical zone. All the defects, alterations, damage and other characteristics that are present in the critical zone and have an influence on its strength are attributed to the critical section (UNI 11119: 2004).
- ***Decay*****:** Change and worsening of the materials' characteristics produced by fungi (EN 1001-2).
- ***Defects (of wood)*****:** Wood growth features that can negatively influence strength and stiffness, and/or the general structural behavior (e.g., the efficiency of joints) of timber members.
- ***Diagnosis*****:** The act or process of identifying or determining the nature and cause of damage and/or biological attack through observation, investigation (including mathematical models) and historical analysis, and the opinion derived from such activities.
- ***Effective cross-section*****:** The part of the cross-section of a timber member that is assumed to carry the load.
- ***Holistic*****:** Emphasizing the importance of the whole and the interdependence of its parts.
- ***Inspection*****:** On-site non-destructive examination to establish the present condition of the structure.
- ***Load-testing (proof-loading)*****:** Test of the structure or part thereof by loading to evaluate its behavior or properties, or to predict its load-bearing capacity.
- ***Mechanical damage*****:** Alteration of timber members or timber structures that appears as mechanical failures, caused by internal or external mechanical actions.
- ***Non-destructive test*****:** A test that has a minor impact on the timber member and that does not influence its load-bearing capacity.
- ***Safety evaluation (assessment)*****:** Evaluation of the safety margins of a structure.
- ***State of preservation*****:** State of a timber member in relation to alterations that are present.
- ***Strength grading*****:** A procedure through which a single timber member can be allocated to a grade that corresponds to a known level of mechanical performance.