INSPECTION TECHNIQUES FOR ANCIENT WOODEN STRUCTURES

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Summary

Throughout Europe and North America is at present recognised the cultural role of ancient wooden structures. In order to be maintained by restoring operators, structural analysts need to know some data about the residual strength of wooden members. But “the assessment of the efficiency (or inefficiency) of a timber structure is one of the central issues of the architectural conservation and at the same time one of the most difficult and complicated problem”. Paper deals with the description of inspection procedure to make a diagnosis on load bearing residual capacity of ancient wooden structures, through visual and instrumental methods. Different methodologies will be analysed, and possible results will be reviewed. Finally future research needs to render the diagnostic methods more reliable will be described.

Foreword

“The assessment of the efficiency (or inefficiency) of a timber structure is one of the central issues of the architectural conservation and at the same time one of the most difficult and complicated problem. Even the approach difficulty and the lack of a studying methodology of a wooden structure, almost always hyperstatic, almost always altered and complicated by successive interventions, must be considered the most important cause of destruction of so many examples. Even now the lack of a technical culture of the timber as a structural material (...) is constant cause of destruction and substantial tampering.” [1].

“The reasons why in the recent past there were negative outcomes in wooden structures restoring are: a general inadequacy of our technical culture to face the structural problems of ancient buildings, conceived and carried out according to principles not connected with our culture; a particular difficulty in the evaluation of the conservation of ancient timber beams and of their actual structural performances; an inadequate knowledge of the structural behaviour, of physical, chemical and mechanical characteristics of this earliest material” [2].

1 The originals are in Italian, translated by the author.
These sentences from two of the most important Italian specialists on the restoration of ancient wooden structures testify how urgent is the need of a real and reliable diagnosis of timber structures.

In fact, most of the ancient buildings such as churches, palaces, castles, theatres and vernacular architecture are considered as a primary cultural heritage, all over Europe. Therefore they are being restored for use as private or, more often, public use. Usually, the wooden structure constitutes a very important part of these buildings, both in terms of load-bearing functionality and of historical and artistic value [3], [4], [5], [6], [7], [8], [1]. In Europe many countries allocate several hundred of million ECU’s for the restoration of buildings and monuments with wooden structures, for example, for next Jubilee celebrations (year 2000) 280 million ECU’s will be allocated for the restoration of the Cultural Heritage, mostly for interventions on ancient buildings, with wooden structures [9]. A large research on construction typologies of historic buildings, related to restoring interventions made during last 50 years, in Italy, France, Britain, Spain and Germany shows that roofs and floors are the most onerous percentage of the interventions in historic-monumental buildings [10].

But the problem to be faced by restorers, is the lack of data about the real load bearing capacity of ancient wooden members, due to a diffuse bad knowledge of wood mechanical properties of architects and engineers, to a lack of appropriated standards about the mechanical grading of “old wood”. From this situation derives the need of an in situ diagnostic technique, based on reliable and quick non destructive technologies, from which obtain some data about the structural characteristics of each single wooden member.

**Diagnostic methods**

The “in situ” diagnosis of ancient wooden structures is up to now described mostly by [11], [12] and [13] for the Italian restoration approach.

It starts from the basic consideration that “generally speaking, the only time passing doesn’t degrade or considerably affect the mechanical characteristics of wood” [11]. The proposed method considers an initial visual inspection on the structure and on the singular members, in order to determine the original characteristics of the considered beam and the eventual modification due to the service conditions, followed by an instrumental inspection that has the scope to check the problems hidden from a direct observation.

Also in Germany [14] and [15], Canada [16] and United States [17] and [18] the diagnostic activity follows a similar path, with some differences in the observation of relevant wood characteristics and in the use of instruments.

**Visual inspection**

The purpose of visual inspection should be the mechanical grading of wooden members [19], but many problems arise [20], [21] and [22] when visual grading rules made for new timber products are used on ancient wooden members. This is due to the frequent presence of defects, nowadays considered unacceptable (e.g. European Standards elaborated by CEN/TC 124). Moreover, recent publications show that ancient wooden members can effectively bear higher loads than expected [23]; underlining the need to clarify the influence of each defect and decay on the real strength of wooden members.
As previously underlined the goal of the visual inspection is the evaluation of the original characteristics of each wooden member and of the variations undergone during the service of the structure.

The first step is a preliminary visual inspection of the whole structure, in order to make a first evaluation of the general bearing and conservation conditions of wooden members and to identify the most relevant parts to be conserved.

In order to make an efficient inspection analysis, operators need to be as close as possible to all the wooden parts of the structure. To do this way a scaffold is essential, as well as good lights to check all the characteristics for visual inspection, and simple instruments to remove dirt from wood surface.

The evaluation of the original conditions of each member starts from the identification of the wooden species, from which basic information about physical, mechanical and durability
characteristics can be obtained. The species can be identified in many cases through a simple macroscopic observation, also because in Europe we can consider that about 10 species\textsuperscript{2} cover the 95\% of all the wooden structures, but in some cases the drawing of a sample is necessary to obtain a surer microscopic identification.

The following step is the identification and the evaluation of most important defects affecting the mechanical behaviour of wood and reducing the typical mechanical performances. Particularly defects to be identified are:

- Knots: maximal dimension and position on the element (intrados, extrados, neutral axis), typology (sound or rotten knot);

- Grain direction: evaluated by means of the shrinkage checks direction. The hardwoods sometimes show localised highly inclined spiral grain, often corresponding to big knots.

- Checks: they can have different origin (shrinkage, ring shake), that must be recognised; the depth and the direction of the checks, referred to the principal direction of the wooden beam, must be measured by means of a thin metal plate.

- Shrinkage's deformations: they are often linked to some defects of the beam, for instance the spiral grain cause a sensible twist, that limit the leaning surface of the beam. Moreover the shrinkage's deformations may cause disconnection in wooden joints or mechanical cracks due to torsion.

This analysis could make possible the grading of the original wooden element according to the visual standards for structural uses.

Then it follows the evaluation of the changes occurred to the members during the service of the structure. This could be due to:

- changes in the equilibrium moisture content of wood due to environmental humidity variations;
- heavy bearing conditions leading to deformations and disconnection;
- deformations under continuous loading, caused by creep;

\textsuperscript{2} Larch, Spruce, Fir, Austrian and Scots pine, common Oak, sessile Oak, white Poplar, black Poplar, Elm, Chestnut.
— attacks by wood destroying insects and fungi;

Figure 4: decorated roofs render difficult, sometimes incomplete, the visual inspection

This part of the diagnosis needs to survey some characteristics of wood, as follows:
— Measure of wood moisture content. A portable electric hygrometer can estimate wood moisture content as far as 6 cm depth with a good accuracy (± 1%). Commonly this measures are made near hazard zones, generally where a moisture condensation risk could be envisaged, thus where wood could absorb water, such as near the insertion point of the beam inside wall or near wood-wood joints. An automatic control of wood moisture content can be established, with a battery data logger, when is well known that environmental thermo-hygrometric conditions frequently change during the year. The moisture content control is a basic parameter to be known by the specialists for the maintenance of the structure, because fungal wood decay depends on wood moisture content.

Figure 5: measure of wood moisture content near the head of a roof beam; in this zone frequently the moisture content is higher than in other portion of the beam.
Mapping, measuring and restitution on an architectonic relief of visible disconnections and mechanical fractures: this is basic for the knowledge of structure stability, even if it must be underlined that often broken wooden beams can still bear loads, as well as the cause of these disconnections and fractures.

Location of fungal and insect attack. Wood decay agents could be a matter of worry for the conservation of wooden elements, depending on the wood zone under attack, fungi or insect agent species, wood species under attack, attack grade, attack phase (still under attack or finished), environmental conditions for wood conservation.

For instance it is well known that some species are more susceptible of fungi or insect attack than other (the natural resistance to the decay of a wood is called durability) and
that within a wood element of a given species, there are zones with a different durability, where generally the heartwood is more durable than the sapwood. Furthermore many decay agents can only attack recently cut wood, and many other have threshold wood moisture content values, above and below which its activity is inhibited. Thus during the inspection it is necessary to evaluate the presence of wood decaying attacks, to identify the agent species, to estimate if the attack is still running on or not and to determine the sound wood section.

Evaluation of the history of each wood element. An accurate visual inspection often allows evaluating if the beams are original (i.e. mounted during the building of the structure) or if they are new or derived from another structure or use. The presence of holes, wanes, no more utilised joints, typical numerical marks can often suggest if a beam has been recycled from different structures. It is also possible to temporally place a wooden element through a surface analysis to see if a saw or an axe has cut it.

Figure 8: the presence of numerical marks (in this case a reverse Y) testifies that the wood-wood joint is original.

Depending on the structure typology some of the quoted determinations could be difficult or even not feasible: this is generally due to access troubles to some part of wooden elements, such as to the extrados of the floor beams, or to a total unapproachableness, such as to the heads of a beam hidden by the walls.

In these situations, and for an inspection of internal part of the beams, it is necessary to activate a "second level" procedure through the utilisation of non-destructive instrumentation allowing the evaluation of the characteristics of "non visible" wood.

**Instrumental inspection**

Visual inspection is normally not able to describe fully and quantitatively the state of conservation of ancient wooden structures. Moreover, the accessibility of critical sites of the structure is often very difficult or impossible. Only apparently the instrumental inspection on wooden structures can be considered as the most objective approach. Being wood a natural material, it is characterised by a high natural variation whose effect, in large wooden beams, is absolutely not negligible.
Thus the role of non-destructive instruments in the diagnostic activity is still not clear: should we use those to estimate mechanical performances of beams or to complete the data obtained from visual analysis?

Many examples are available for the utilisation of different methods in order to calculate the stiffness of wooden beams. The most generally used method is probably the measurement of ultrasound velocity parallel to the grain, for which many examples can be quoted both for grading of “new” material [24] and [25] and for in situ or “old” material analysis [18], [26], [27] and [28], but the method seems to be less useful when used in “in situ” analysis because of non-homogeneity of cross sections and because of the frequent presence of surface decay caused by insects.

Among the NDT (Non Destructive Testing) methods special attention seems to be paid to dynamic techniques in the acoustic domain, because of their execution speed, relatively easiness to use and low equipment costs. Two NDT techniques have demonstrated their reliability and efficiency: the transverse (or longitudinal) vibration technique (TVT) and the stress wave technique [29]. A strong correlation with a four static bending test in a wide range of specimen size has been observed (structural timber or specimen with a length-to-depth ratio as low as 16). In comparison with other non-destructive techniques methods (ultrasounds, visual assessment...), the TVT gives the best correlation with strength of structural timbers. This technique allowed determining MOE with a very good repeatability and accuracy and can be expected as an efficient grading tool [30] and [31]. The problem with this technique is the significant influence of the boundary conditions. For in-situ assessment of wood members it seems to be not suitable. But for the measurements of a beam out of the structure (free-free beam i.e. beam with no constraints) this technique has proved its efficiency, reliability and rapidity. It will serve to compare the TVT MOE and the evaluation of the defects with the values and parameters obtained by others NDT techniques used in situ [32] and [33].

Some papers try to find correlation on strength and stiffness characteristics with punctual hardness or drill resistance characteristic, but the results show that these methods are truly reliable just for an early evaluation of basic density of the wood rather than for mechanical grading of the beam, mostly influenced by the extent and location of its defects [34] and [35].

Other methodologies try to use instrumental results to determine the presence of hidden defects or lacunas into the wood in order to complete the observations done by visual analysis to determine the strength grading [15], [23] and [36].

In order to obtain the data for this goal two types of instrument are actually used: the ultrasound velocity (or attenuation) perpendicular to the grain and the resistographic method.

The first one is quite speedy and could give information through anomalous ultrasound velocity values, without any specification about the nature and the dimensions of the anomaly, while the resistographic inspection is considerably more time consuming and the utilised instrument is bigger and heavier, but the obtained data are more precise. Moreover the utilisation of ultrasound instruments on in-situ wood inspections is conditioned by the surface state of the artefact. Therefore when insect has altered the sapwood, any ultrasound control become useless.

Resistographic inspections are made by means of a portable electronic instrument called Resistograph®, which results can give information about the state of non-directly visible wood portions.

The Resistograph® is a thin needle drill (diameter of the hole about 3 mm), that can inspect, depending on the model, a depth of 280 or 410 mm, equipped with direct current supply unit and with a thermal paper printer. Inspection data can be directly read from the plot emitted by
the printer or stored by a data logger built in into the printer, extracted as a file and then elaborated through a proper software (Decom®).

The drill is the mechanical part of the instrument and consists of two electric engines giving the needle a constant speed rotation and forward movement (adjustable by the operator, depending on wood species, between 5 and 50 cm/min).

Each mm/25 forward the data logger automatically acquires the electric energy consumed by the two engines; this value is strictly correlated with the penetration resistance opposed by drilled wood, then mostly with its density. The resistographic inspection produces as a result a x-y plot with the penetration depth in abscissa (1:1 scale), while the ordinate shows the penetration strength values through instrumental units. These values (as plots or numbers) can be evaluated also during the inspection, referring those to other data obtained during previous experiences during drilling on sound wood.

The operator everytime decide the section, or better the straight line, to be examined. Generally the advancing direction of the needle is perpendicular to the grain direction (radial, tangential or intermediate, as regards to the rings) or with a more or less oblique angle inspecting the heads of the beams leaning into the walls.

During inspection on wooden structures the resistographic drill can be used for the following evaluations:

— Section of the beam: when is not possible to directly take the measure of the section of a beam (for instance on lacunar ceiling) the resistographic drill can give measure as long as 40 cm.

![Figure 9: resistographic plot performed perpendicularly to an apparently sound beam. Considering that the drill starts at right, the plot shows, after 4 cm of sound wood, a hollow taking up almost all the section, excluding the last 3 cm. It is also possible evaluate that the original section were about 26 cm.](image)

— Remaining section of the beam: an attack by wood decay agents causes a lower resistance of degraded wood that is showed by the resistographic plot.

— Growth ring pattern: a drilling made along the radial direction of the stem produces a plot showing the profile of growth ring pattern; this is due to the fact that the instrument can check the density difference, that can be found on many wood species, between the earlywood (less dense) and the latewood (more dense). The knowledge of the growth ring pattern can be useful because it can characterise the wood species (as for larch and Norway spruce) and it can also give information about the mechanical strength of the beam.
Figure 10: resistographic profile performed along the radial direction of wood on a softwood beam. The density difference between earlywood and latewood displays on the plot the growth ring pattern.

Presence of defects not exteriorly visible: as previously noted, the passing of the drilling needle can record any resistance (density) difference within wood. This kind of deep inspection is the only method that can give reliable data about the presence and the dimensions of inside defects like decays, resin pockets, bark pockets, ring shakes and other.

Figure 11: use of resistographic drill to check the state of the head of a beam leaning into a wall.

State of the heads of the beams inserted into the walls. Many direct experiences, as well as many bibliographic collations about restoration, notice that the heads of the beam are a highly exposed to the risk of decay. In this situation, the microclimatic conditions are often very wet and in consequence the biotic attack (fungai wood decay) risk is higher, also as a
consequence of bad restoration practices that don’t allow the necessary air circulation around the wood. Therefore the inspection made near the heads of the beams inserted into the walls must be considered one of the most important phases of the instrumental inspection.

At present no experience exist about a combined use of the two instruments: in many cases it could be envisaged a preliminary quick inspection with ultrasound, perpendicular to the grain, followed by more precise determination through resistographic inspection on the heads of the beam and where the ultrasound values were anomalous.

**Future work**

The diagnostic survey needs an interdisciplinary work: many professional figures (Architect, Civil Engineer, Wood Technologist) could give their own contribution in order to clarify the preservation and static state of the structure. The research and applied activity up to now performed allowed the formulation of a diagnostic protocol, tested on many study cases and proved as an efficient, reliable, practical and cheap instrument.

But, as previously somehow noted, the described procedure needs several improvements, only obtainable through time and money consuming research work.

Firstly, it must be underlined that no standardised procedure is available yet, both at national and European level. Moreover, the field instruments being used need an improvement in terms of precision, reliability and easiness of use, due to the fact that the accessibility of the points of measurement is normally difficult and that wood is a very anisotropic and variable material.

But to reach that goal a previous research work must be performed, considering that the conservation of ancient wooden structures requires appraisal’s procedures which must take into account not only those rules available for the design of “new” timber structures, but also peculiar technical aspects mainly dealing with the assessment of visible and hidden timber defects, biological decay, mechanical damage, effectiveness of joints, effectively load-carrying sizes, effective stresses and deformations induced by the actual loading conditions, environmental (biological) hazard, in order to appraise as accurately as possible for strength and fitness for use both each structural member and timber structure as a whole.

During the last years a great deal of technical work has been performed at European level in order to build up harmonised rules for the design of timber structures. ENV 1995 “Eurocode 5 - Design of timber structures” was the main outcome of this effort, accompanied by a comprehensive set of standards concerning the visual and machine strength grading of structural sawn timber and wood based panels, the static load testing, the determination of characteristic values of mechanical properties and density, the development of a strength classes system, etc. (EN 384, EN 518, EN 519).

Although of invaluable importance for the future of timber as a modern structural material, it is however recognised that the standards and reference documents produced are not very helpful to the engineer called to meet decisions on the appropriate design values to be adopted for in-situ timber members [37]. Further research is therefore absolutely needed, in order to develop specific standards in the medium term. In our opinion most important direction should be:

- to allocate the pieces into appropriate grades through “ad hoc” developed visual grading and non-destructive testing;
- to test to failure the selected samples according to “ad hoc” developed test methods;
- to derive density, strength and stiffness characteristic values and/or allowable stresses according to modern semi-probabilistic procedures.
Last problem to be faced in order of time is the assessment procedure. The wide variety of structure typology, the frequent hyperstatic configuration and the natural high variability of wood make the assessment of an ancient wooden structure more difficult than for other kinds of structures. The technical principles introduced by the Eurocode 5 rules and the prENs (TC 124) related to grading of structural timber appear to be useful to represent the specific features of the ancient timber structures, when adequate modification factors are developed. But this is a problem to be considered by structurists, while the author is just a wood technologist.

Bibliographic References

12. UZIELLI L. - Valutazione della capacità portante degli elementi strutturali lignei. L’Edilizia, 12/92. 753-761.
15. RINN F. - Verbesserte untersuchung des zustands hozner konstruktionen. BDB Nachrichten Nordhessen/Thuringen, 2/95, 37-45.
engineering Division - Historic preservation working group. Minneapolis, USA, June 1996.


24. SANDOZ JL. - Mechanical assessments of conical roundwood for swiss spruce. int.Conf. on wood poles and piles, Oct. 25-27, 1989 Fort Collins, Co USA.


28. BALDASSINO N., PIAZZA M., ZANON P. - In situ evaluation of the mechanical properties of timber structural elements. 10th International Symposium on non destructive testing of wood. August 1996, Lausanne, Switzerland.


31. CASSAN P., BAILLERES H. - Mechanical characterisation by a transverse vibration technique: a perspective for grading. IUFRO ALL Division 5 Conference, Subgroup 5.02.01, July 7-12, 1997.


