Restoring timber structures - Inspection and evaluation

STEP lecture D3
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Objective

To present the various objectives and methods for the inspection of existing timber structures, as a basis for the evaluation of their safety, serviceability and prevention of future degradation.

Summary

Existing structures, whether old or new, must periodically undergo a thoughtful inspection and evaluation of their safety and serviceability. For timber structures the accomplishment of this difficult task implies the involvement of different experts: wood technologists, engineers, architects and possibly other experts cooperating to check the condition of each structural element, evaluate the serviceability of the whole structure and prevent future degrade. This lecture describes the wood technologist's various methodological approaches.

Introduction

Conservation and restoration of existing timber structures is a relatively new idea, the implementation of which requires a multi-disciplinary approach. In the pool of experts (architects, engineers, restorers, etc.), a basic role is played by the wood technologist; in fact, through a careful examination of each structural member and joint, his duty is to derive accurate information pertaining to the properties, performance and condition of the material, and also to determine realistic boundaries within which the designer shall make his calculations.

In general, the inspection of an existing timber structure has the following main objectives:

- to provide the information needed by the structural engineer in order to assess if the strength and the stiffness of members and of connections are satisfactory for structural safety in the intended use;
- to point out parts which may need specific reinforcement, substitution, or other types of intervention;
- to evaluate decay factors which may have affected the structure, (in part or in whole) and which may affect it in the future; and to identify and recommend appropriate, remedial measures to prevent such risks from recurring;
- to cooperate toward the identification of the structural behaviour of the construction work; in the case of structures having historical artistic or cultural value, to cooperate toward a better knowledge of its history, manufacturing techniques etc.

The means to achieve these objectives (concerning all the load bearing elements) are the following:

- to assess the timber quality: ascertain the wood species and its main physical and mechanical properties, including defects and anomalies;
- to detect existing decay or damage suffered in service;

- to assess the risk of decay or damage in future;
- to assess the effective cross section(s), and their strength and stiffness characteristics.

Factors influencing the state of the structure

Since wood is a material of biological origin, its properties show a much greater intrinsic variability than other quite homogeneous and almost isotropic structural materials, such as steel and concrete. Therefore, no reliable methods exist today which can accurately predict the strength of an individual structural timber member. Grading methods and testing procedures have been developed for the determination of characteristic strength values of newly sawn timber, which are based on the statistical distribution of a group (or grade) of timber members in which the actual strength of an individual member cannot be exactly assessed. Moreover, the uncritical extension of rules and values given in structural design codes to old timber members may be inappropriate, for example because:

- it is sometimes impossible to visually inspect all faces over the whole length of the members in-situ;
- wood can be affected by decay/damage, which in general is excluded from new timber by grading rules;
- old beams are often of large cross-section, which include the pith in a more or less central location.

Gross mistakes in the assessment of old timber members can be avoided by identifying and separating, through different surveying methodologies for each case, the partial contribution of every possible source of variability, and then by operating a final synthesis combining together those results.

As a minimum, the following sources of variability shall be considered by the surveyor for evaluation.

Original timber quality

A basic characterisation of timber quality can be achieved through the assessment of the following parameters: wood species; provenance (if available); type of timber (round timber, sawn timber, beams, joists, planks, boards, cross-section with pith included or not, quarter sawn, flat sawn, etc.); sapwood and heartwood distribution, density (average value at 12% moisture content), ring width, slope of grain, location and extension of natural defects (knots, fissures, checks, ring shakes, resin pockets, compression or tension wood). The influence of each of these parameters shall be assessed based on procedures similar to those developed for the grading of newly sawn timber.

Service conditions

Biological degradation: the wood technologist shall detect biological degradation, indicating with precision its origin (fungi, insects, bacteria, marine organisms), causes, effects and development. It should be pointed out that ordinarily it is necessary to proceed to a refined identification of the wood destroying organisms, because of the broad variability among different species within the same group (life cycle, kind of decay, influences on timber structural properties, prevention strategies). For example, it is essential to distinguish between the discoloration due to stain fungi (neglectable effect on wood strength) from that caused by incipient attack of decay fungi (responsible for brown, white or soft rot, i.e. the complete destruction of the wood molecular structure); or between the exit holes of *Anobium* and *Lyctus* beetles, in order to avoid expensive and dangerous mistakes.

Age: small clear wood small specimens extracted from old sound timber members and tested to failure (bending, compression, impact, etc.) show no significant differences in strength and stiffness values from comparable new material (Jessome 1965, Kuipers 1986, Cristelli F. 1986, Ehlbeck and Görlacher 1987, Rug and Seeman 1991). In the absence of decay, it is in fact (up to now) impossible to discriminate an "age effect" on wood from test data. This does not mean that wood did not undergo any chemical modification in the course of centuries: the amount of crystalline cellulose, for example, seems to decrease with time (Borgin et al. 1975), but simply that the range of strength values obtained from this material fits almost perfectly into that obtained from new wood specimens of the same species and quality. Hence, the surveyor shall not include timber age (no matter how defined) among his assessment parameters.

Loading conditions: they shall be considered mainly by the engineer according to the structural design codes. Nevertheless, the surveyor should be aware, for example, of the emphasis to give in his report to large deflections in timber bending members, trying to estimate if these are only due to elastic deformation or partly to hygro-mechanical phenomena (creep).

Moisture content: wood is hygroscopic and its moisture content affects almost every property considered in the design of timber structures: strength, stiffness, durability, dimensional changes (shrinkage and swelling), shape stability, etc. It should be remembered that all design values are referred to timber at 12% moisture content and modification factors for different actual moisture content values are given. Surveyors shall put maximum emphasis on a careful assessment of timber members in respect of their past, actual and future relationships with surrounding water (air humidity, rainwater or pipe leakages, condensation, capillary water present in wet walls, etc.), reporting in detail every localised or general situation in which a timber moisture content exceeding 18 - 20% has been measured or is likely to be attained, with subsequent risks of biological degradation due to fungal attack (see below).

Temperature: the effects of temperature in timber structures are very often overestimated by engineers and architects experienced with other materials such as steel, which show a significant thermal expansion. As a general rule, effects on timber strength can be ignored for temperatures under 60 °C. On the other hand, changes in temperature result in changes of wood moisture content, with subsequent dimensional changes due to shrinkage or swelling, which are much greater than thermal expansion or contraction (see below).

Radiations: the most common case is that of timber irradiated by the sunlight. Ultraviolet rays can modify the structure of wood only in the very superficial layers (one *mm* depth or so), causing discoloration (greying) and a sort of carbonization in the worst cases. The underlying wood mass is protected and therefore not affected. Other radiation types such as gamma-ray, x-ray, microwaves and similar, can modify or even destroy the intimate wood structure, but this may happen at a dose rate far beyond the thresholds normally encountered in civil engineering.

Maintenance and repair history

It is a matter of fact that the worst damage in old timber structures often occurs as a result of improper restoring interventions. For surveying purposes the following aspects shall be checked:

- Modifications in the use of the building or of the structure.
- Unfavourable micro-climate alterations: particular care shall be drawn to insufficient ventilation of all the surfaces of the timber members, to the "sealing" of beam ends into the walls, to the possible formation of condensation as a consequence of roof waterproofing (asphalt coatings, vapour barriers and similar) or air conditioning units installation.
- Insufficient routine maintenance: any structure must undergo periodic maintenance work, and timber structures are no exception. Actually, many timber structures have been "forgotten" for decades. A slow accumulation of moisture, dirt, decay and mechanical damage may have cumulated into a serious general degradation, whereas timely and qualified maintenance can easily preserve the original structural integrity for centuries.
- Improper repair and restoration: special attention shall be drawn to the compatibility of timber and other materials often used for repair. Under "compatibility" both physical-mechanical characteristics and static-dynamic behaviour of the wood-other material combination shall be ranked. The commonly used reinforcing/repairing techniques often do not take into account to the necessary degree the basically different hygro-thermo-mechanical behaviour of steel, concrete, epoxy-resins and other structural materials in respect to wood and its anisotropy. Another common source of problems may be the beloved but strongly censurable plugging of fissures with wooden wedges (or even their sealing with epoxy resin): these longitudinal fissures derive from the natural shrinkage of drying wood and their width shall be free to continuously vary according to the climatic changes and related variations in the wood equilibrium moisture content (EMC). Their plugging with a stiff material will prevent their physiological movements, hence inducing stresses in the material and the opening of new fissures. It is strongly recommended to avoid plugging or - if absolutely necessary for some reason - to execute it with a soft and yielding material.

Inspection levels

The restoration of timber structures is very often part of a more general intervention on buildings, where dimensions and historical importance make it advisable to split the surveying work into two separated steps:

- a preliminary inspection aiming to give a general idea of the structure's condition and of the actual need for further detailed investigations;
- a detailed inspection, leading to the assessment of each individual timber member in the structure.

First level inspection (general evaluation)

Objectives: preliminary assessment of whole structures without assessment of individual timber members; recommendations regarding intervention priorities (priority classes).

Minimum feasibility conditions: the surveyor shall be provided with the plans of the relevant parts of the building; the structure must be accessible and the faces of the timber members should be cleaned and well illuminated; for the best results, coatings should be removed from wood surfaces.

General visual inspection: wood species shall be identified to the degree of accuracy permitted by the visual inspection: a skilled wood technologist should be able to discriminate - in normal cases - at least softwoods from hardwoods. In some cases, certain groups of wood species can be accurately identified by visual inspection thanks to their peculiar anatomical features, such as Oak (gen. *Quercus*), Chestnut (gen. *Castanea*), Elm (gen. *Ulmus*), Fir and Spruce (gen. *Abies* and gen. *Picea*), Pine (gen. *Pinus*), Larch (gen. *Larix*). Average timber quality shall be visually assessed, taking into consideration mainly knots, fissures, slope of grain, apparent decay and/or damage.

Expected biological risk evaluation: through a critical examination of the environmental conditions, the surveyor will evaluate the risk of biological attack and place the whole structure under assessment into one of the service classes foreseen by EC5. Timber structures exposed (or having been exposed in the past) to high biological risk conditions should be rated under a high priority class even if their actual conditions seem to be good.

Apparent decay/damage evaluation: the surveyor shall identify and report any sign of wood decay, even at incipient stages, giving details about the available technical means to stop its worsening.

Grading of the structure according to priority classes: on the basis of the above mentioned operations, the structure will be allocated (as a whole) into one of the three following *priority classes*:

Class "green": low priority of intervention; as far as timber is concerned, the structure is in good condition; biological risk is low; eventual decay is in incipient stages, no longer active and restricted to uncritical locations; only routine maintenance is required.

Class "yellow": medium priority of intervention; timber members suffer some decay; damage and/or biological risk is high; further detailed investigations and restoring interventions are required in the short term, even if the structure is not under immediate danger of collapse.

Class "red": high priority of intervention; timber is affected by decay in critical locations; the structure is in immediate danger of partial or total collapse; further detailed investigations are required, but their execution will be possible only after provisional reinforcing/repairing interventions in order to comply with safety criteria.

Deliverables: the surveyor should deliver at least a thematic map, in which priority classes are represented on the building plan by appropriate colours: green, yellow, red and grey (this fourth colour is required to indicate those structures intended for visual assessment, but excluded from it because they were not accessible for any reason) and a technical report on the general condition of the timber structures under inspection, including recommendations about eventual need of further detailed analysis or other types of intervention.

Second level inspection (detailed evaluation)
Once priorities have been well established, a detailed inspection might be required for those structures showing problems to such a degree that more information on residual sections and/or the effective performance of timber members is needed.

Objectives: to assess each individual timber member and each structural joint of a given structure; to provide the engineers with strength and stiffness values consistent with actual member's condition; to assess the effective residual sections of each member affected by decay.

Minimum feasibility conditions: the same as for first level inspection, plus access with eyes and hands over the whole length of each member.

Detailed visual inspection: if required, wood species shall be identified through microscopical analysis of fragments extracted from the wood member under assessment; wood defects shall be evaluated in any cross-section or length considered as relevant by the surveyor; the same for wood decay evaluation.

Timber moisture content measurements: one or more measurements of wood moisture content will be performed with an electrical resistance moisture meter provided with insulated electrodes, in order to determine an average moisture content value and moisture content gradient, localise wet spots, condensation formation, etc.

Residual cross sections assessment: through both visual assessment and basic instrumental techniques such as probing test, splintering test and sounding (beating with a hammer) test, the surveyor should be able to plot on the paper the effective member cross section(s) determining: pith location; heartwood and sapwood distribution; checks, ring shakes and shrinkage fissure's development; location and extension of decayed wood zones and/or cavities; knots and resin pockets location and extension.

Joints assessment: timber-to-timber joints shall be assessed mainly through a careful visual control of decayed areas or disconnections; timber-to-other material joints shall be examined for compatibility aspects (as already described above). The assessment should be made on each joint or at least on a significant sample, upon agreement with the pool of experts.

Evaluation of previous restorations (historical and/or recent): this task should be undertaken preferably together with other specialists, in order to assess the actual performance of restored structural parts, the compatibility between timber and other materials used, the expected serviceability and durability of the intervention and any recommendations for improvement.

Hypothesis on future decay and/or damage development, including recommendations to prevent them (preservative treatments, measures against fire and against moisture uptake, etc.)

Deliverables: the wood technologist shall deliver at least:

a detailed map of wood decay, and a set of drawings indicating:

- the graphical reconstruction of one or more relevant residual cross sections for each timber member;

- the graphical reconstruction of actual joints;

a technical report including at least a detailed description of:

- the inspection results;
- the timber structural quality (for each member);
- recommendations for the prevention of future decay;
- provisions to obtain serviceable and durable timber structures complying as far as possible with EC5 and/or other building regulations.

In-situ testing techniques

A careful visual assessment, coordinated with basic test procedures such as probing, splintering and sounding and supported by a microscopic wood species identification, make it possible - for a skilled surveyor - to obtain results to the degree of accuracy normally needed by engineers and architects.

Additional information can be in some cases obtained through non-destructive or slightly-destructive instrumental techniques. Nevertheless, it should be clear that measurements on timber members are always affected to a significant degree by uncertainty due mainly to:

- variability of wood properties within the timber member;
- oversimplified fundamental hypothesis of non-destructive methods in respect of the actual behaviour of wood material;
- difficulties in practical measurement execution in-situ (and often also in the laboratory).

Serious surveying work will then have resort to non-destructive testing preferably as a subsidiary way to strengthen (or weaken) the hypothesis arising from the visual assessment.

Commonly used instrumental techniques are the following:
Static loading: measuring the modulus of elasticity of a member by static bending techniques is the foundation of machine stress grading of newly sawn timber. Also for in-situ timber members (and, with appropriate modifications, also for structural systems, for example floors), it is possible to compute an average modulus of elasticity by using well known fundamental equations and to infer strength values through the relationship existing between these two quantities. In some cases a clever approach may be the adoption of a sort of "unloading test", i.e. a procedure where the modulus of elasticity is derived by measuring the elastic spring-back of timber members after the removal of existing permanent loads.

Endoscopy: this technique is sometimes used to observe hidden faces or even internal cavities of the wood member, hence shall be considered as an extension of the visual assessment. In connection with drilling techniques (see below) it can be used for the assessment of partially decayed cross sections.

Thermography: often proposed by beginners in wood structure surveying, it is seldom useful, because of the very low thermal conductivity of wood.

X-ray, gamma-ray, computer tomography, nuclear magnetic resonance: these techniques make possible a very accurate internal scanning of whole timber members. Today their use is restricted to a few laboratories and costs are too high for an extensive utilisation. Nevertheless, portable units intended for decay detection in standing trees and timber beams are currently in promising development.

Vibrations: free and forced vibrations (transverse and longitudinal) have received considerable attention for non-destructive testing of in-situ timber members. The aim is the same as for static loading tests: to compute a modulus of elasticity (in this case from selected vibration frequencies and related amplitudes) and from it to infer strength values.

Acoustic emission (AE): not extensively used on structural timber, it relies upon the application of stress to a member and the analysis of the stress waves generated by it. In connection with static loading techniques, it could be used to locate highly defective cross sections (DAE: defects acoustic emission, Bonamini and Togni 1994), under the hypothesis that failure in structural timber members may occur by stress concentration in small areas (for example, around a knot) far below the elastic limit of the whole section, causing a localised AE (Bonamini and Togni 1994).

Stress waves (ultrasound, impact): speed of stress waves through the timber member is used either to detect decay (transverse propagation) or to compute a dynamic modulus of elasticity (longitudinal propagation). If accurate data about wood density are available, and coupling problems between wood and transducer's steel are carefully overcome, stress waves techniques can provide useful indications. Both conditions are often quite difficult to meet on site.

Pilodyn: a hardened steel pin is driven into the wood by a spring-loaded device. Depth of pin penetration (after one or more blows, according to the instrument model) is used as a measure of degree of surface degradation. Results are affected by test location within the member, wood anisotropy, wood density, percentage of spring- and latewood, operator's skill.

Drilling resistance: specially built electronic controlled drilling machines rely upon the relationship existing between wood density and the rate of penetration of the bit. These machines can bore up to 400 *mm* depth, automatically plotting on a chart a pattern from which density variations can be easily detected. Useful for internal decay assessment and for ring width assessment, these instruments give information related to the restricted area under test, not immediately extensible to large zones.

Displacement transducers and strain gauges: these devices are in some cases used during loading tests in order to evaluate local strains, slip in joints, etc.

Hardness: hardness tests on the faces of wood members can provide some information on local surface conditions of the material. Strength values for the whole member can be derived, through repeated tests on different points of the same member, only by very rough approximation.

Screw withdrawal: the force needed for extracting a screw shows good relationship with wood strength at that point; hence this technique can provide useful information on surface or deep deterioration of members.
The same limitations apply as for Pilodyn, drilling and hardness devices about

the possibility of inferring strength for large members,

Conclusions

Timber structures assessment is a complex task. Automatic devices capable of deriving from one or two measurements a complete set of strength and stiffness properties are not available, hence the visual assessment should be the first and the last step of the inspection work.

Systematic approach, clear ideas about wood microscopical structure and timber macroscopical behaviour and last but not least a good deal of patience and scientific humility will help in reaching valuable results with inexpensive means.

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