Strategies for the evaluation of existing timber structures: Challenges, problems and solutions

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ABSTRACT: To perform a reliable assessment of existing timber structures it is necessary to take into account a multiscale and time dependent behaviour. Unfortunately simple and straight forward analysis usually conducted uses only the information available to the design of new timber structures. In the last decade some important advances were made in the fields of guidelines for the assessment of existing timber structures, new survey techniques (including semi-destructives techniques), new data treatment models and regulations. However the uncertainty about the wood material and its properties, the behaviour of timber connections and the way the different survey methods can be efficiently used makes extremely difficult to provide reliable data to the engineer responsible for performing a safety and serviceability analysis of an existing timber structure. As a result of this procedure the final decision is often based on high cost repair/reinforcement works or the demolition of the entire structure even if that structure performed satisfactorily for decades. The present paper discusses different aspects to take into account while performing a survey to a timber structure, detailing some procedures to be followed to obtain information on relevant variables (strength of structural members and connections) and possibilities to address the effect of biodeterioration, time-dependent problems and available data treatments methods. The discussion is supported by recent results on the analysis of structural timber members and new paths based on activities foreseen to be conducted within a research project that will be launched in 2016.

1 INTRODUCTION

A broad discussion is being take regarding the suitability of design codes for the assessment of existing structures or if instead specific rules for existing structures should be produced. At moment the need to adopt specific rules seems to generate a large consensus in the scientific and technical community. The assessment of existing structures is the concern of various documents already published (CIB, 2010, Rücker, et al. 2006, Diamantidis, 2001). Also the mandate M/515 supporting the amending and extension of the scope of existing structural eurocodes previews that new codes will include assessment, re-use and retrofitting of existing structures as already happens in part 3 of Eurocode 8 (Luechinger, et al. 2015). Following this line of reasoning, recently some standards had been published (SIA 269/5 and NEN 8700) covering different types of structures or providing a common framework for the assessment of existing structures (ISO, 13822).

Regarding historical timber structures scarce or even none information is available about the criteria for selecting timber member and the design of connections at the time of erection. This situation also occurs strangely in some recent constructions (even when involving glued-laminated timber). The lack of prior knowledge about structural information and uncertainty about the reliability of new data from the application of non or semi-destructive testing

(NDT/SDT) methods in-situ often result on the straightforward use of tools available for the design of new constructions, i.e., application of current visual strength grading standards combined with the application of semi-probabilistic structural rules (e.g. Eurocode 5). Eurocode principles (characteristic values and safety factors) allow to conservatively handling timber variability and the result can be assumed as safe (even overconservative) if a carefully structural and geometric survey is carried out. However although this approach is considered reliable - "Ability of a structure or structural element to fulfil the specified requirements, including the working life for which it has been designed" - it can lead to unnecessary expensive rehabilitation or demolition (and reconstruction) works.

A truthful assessment of any timber structure implies a careful consideration of five crucial parts in the decision making process, Figure 1: 1) gathering of information about the structural elements and connections performance; 2) allocation of structural properties; 3) the need to take into account time-variant effects; and, 4) definition of the required level of structural performance. Finally after completing these parts a choice has to be made regarding the structural analysis models (step 5) to apply. All these parts have an impact on the decision-making process and are included in different assessment phases described by several flowcharts diverse according to the complexity and detailedness of the investigations to be carried out (ISO 13822, Diamantidis 2001).

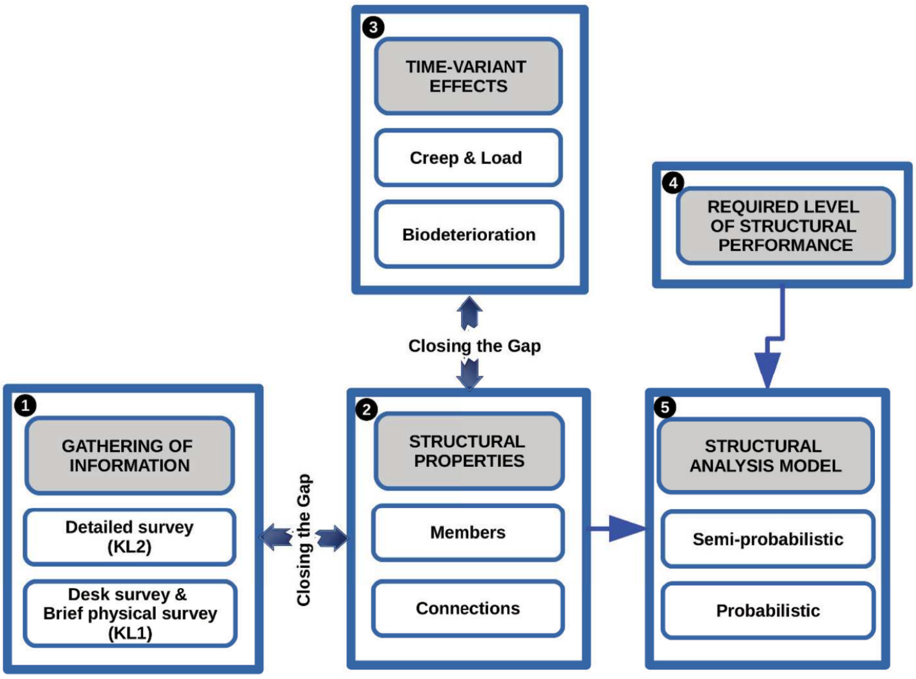


Figure 1. Parts to be considered for safety and serviceability assessment of timber structures (identification of gaps that need to be closed and that will be studied within ProTimber project). KL – Knowledge Level.

The project ProTimber will follow the work already carried out by the project team and will be particularly focus on closing the gaps still existing in procedures to obtain reliable new data (part 1) and to cope with time-variant effects (part 3), both factors affecting significantly the short and long-term timber structural behaviour. Thus ProTimber main goals are to tackle four main issues:

- Obtaining reliable predictions of the short-term resistance of structural timber members;
- Probabilistic assessment of structural joints;
- Assessment and modelling of time-variant effects;
- How to combine all information into a probabilistic assessment model for timber structures.

In section 2 some of these topics are discussed.

2 ASSESSMENT OF EXISTING TIMBER STRUCTURES

Safety and serviceability assessment involves considering the effects of loads (S_d) and the resistance of the structure and its components (R_d) and ensuring that the former should be inferior to the latter ($R_d \geq S_d$) with an acceptable reliability index (β). The verification of safety and serviceability limit states by semi-probabilistic models (e.g. Eurocodes) is based on the definition of characteristic values for load and strength (or stiffness) and associated to that the partial safety factor for load and material properties. Regarding resistance different factors are or can be applied to the characteristic values to obtain the design resistance (or in the case of existing structures the verification resistance value), eq. 1.

$$R_d = X_k \times \frac{1}{\gamma_m} \times k_k \times k_{time} \times k_{con} \times k_{aging} \tag{1}$$

Where:
R_d- Resistance taken for assessment
X_k – Characteristic value of resistance
γ_m – Resistance safety factor
k_k – Size (volume effect)
k_{time} – Factor taking into account the long-term effects of load and moisture content; $k_{time} = k_{mod}$ for strength or $k_{time} = 1/(1+k_{def})$ for stiffness
k_{con} – Conservation factor (decrease of resistance due to insect or fungi biodeterioration)
k_{aging} – Reduction of wood properties given the load and environmental action upon the structure during its existing working life

Eq. 1 shows that additionally to those factors already affecting the characteristic value (γ_m, k_k, k_{time}) by Eurocode 5 other two crucial factors have to be considered (k_{con} and k_{aging}). Both load and resistance components have to be evaluated (prior information based on historical or assumed design values and new data from testing). In the case of load although imposed load can be lightened other changes are dependent upon a decision on a shorter design life time (Vrouwenvelder, 2010). Load aspects will not be dealt in the present paper. The gathering of information on relevant parameters to define resistance is characterized by uncertainty and the need to address combination of equality type, inequality type, direct and indirect information (Fink and Kohler, 2015). The significant level of uncertainty is satisfactorily addressed by probabilistic models by allowing associating to an event a certain level of probability of failure (P_f), eq. 2. The consideration of a certain level of failure results in a more informed decision-support processes.

$$P_f = P(R < S) = \Phi(-\beta) \tag{2}$$

Where: β is the target reliability index and Φ(…) is the standard normal integral

β is associated to three consequences classes in Eurocode 0 (EN 1990) – CC1, CC2 and CC3 - and this index related to new or existing constructions. Also by considering and taking measures that human safety is not involved a fourth class can be considered (Vrouwenvelder 2010), Table 1.

Table 1. β index as function of consequence classes (CC), type of construction and wind action dominance (Vrouwenvelder 2010).

Consequences class	Minimum reference period for existing buildings (years)	β-new		β-old	
		wn	wd	wn	wd
CC0	1	3.3	2.3	1.8	0.8
CC1	15	3.3	2.3	1.8*	1.1*
CC2	15	3.8	2.8	2.5*	2.5*
CC3	15	4.3	3.3	3.3*	3.3*

CC1 to 3 – Consequences classes as defined in Eurocode 9.
CC 0 – as class CC1 but no human safety involved.
* - in this case is the minimum limit for human safety normative.

2.1 *Gathering of information*

The gathering of information about structural timber members and connections (including conservation) is a crucial step and is normally conducted in two stages. First it is carried out a simplified approach according with principles well described in existing documents (Cruz, *et al.* 2015; UNI11119 and SIA, 2011). Common initial reference properties are allocated to all timber members (X_k), the behaviour of timber joints assumed as pinned joints and time-variant effects considered as for a new structure. Representativeness questions as the number of members to be graded are left to the decision of the expert. This simplified view is used to perform a first structural analysis using a semi-probabilistic model (e.g. Eurocode 5).

Different outcomes can came out of this first assessment which can be resumed in two scenarios: 1) no more information is needed (either because the structure is clearly fit or unfit to use); 2) some doubts are raised and more detailed investigation is decided to be carried out.

In this last situation the preliminary visual survey and structural analysis should provide information about the critical areas in the structure, members or connections, where the onsite detailed inspection should be carried out.

The strategy for updating the initial reference properties of timber members go through two routes for a closer appraisal of the real quality of timber members and connections. Regarding the first route two methods can be followed to update the resistance (update X_k): 1) enhancement of visual strength grading at the identified critical parts of the structure; and 2) application of new NDT/SDT methods.

The first method relies on the knowledge about the type and level of stress applied to a particular timber member and the location of defects in relation to the level and type of stress in the element (Cruz, *et al.* 2015). The advantages of this procedure was reported for the renovation of Colonial Buildings built in 1889 where it was possible to save at least 60% in construction works (and minimize the level of intervention) (Williams, 2009). This fact supports the feeling that conservative assessment may as opposite to conservative design lead to significant costly options. However, specific procedures to be follow for upgrading visual information are still missing. The second method (using other NDT and SDT methods) allows obtaining new data which is independent from visual strength grading (Machado, 2013).

At this level the perspective of a timber member can maintain its view of homogenous element (no lengthwise resistance variation) subject to a uniform stress along its lengthwise, Figure 2a. In the case of ProTimber however this view changes to a heterogeneous element subject to a nonuniform stress, Figure 2b. This multi-scale approach (vision followed by ProTimber and also considered in model Code) subdivides the member in multiple elements and using the information of each element (visual and mechanical) to predict the overall performance of the structural member.

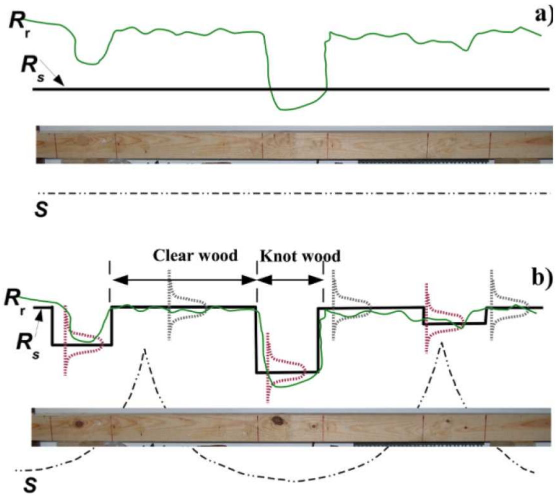


Figure 2. Changed of the view of a timber member from: a) homogeneous to b) heterogeneous. R_r – Real resistance profile; R_S – Simulated resistance profile; S – Load profile.

The new information obtained from test conducted onsite should then be used together with the information obtained from visual grading (Feio and Machado, 2015) to deliver a posterior predictive distribution of the variable. Bayesian inference is a current tool used for updating prior information, P'(θ), (obtained from the first survey) with new information $\hat{x}$ to which is provide a certain weight (belief) as function of their likelihood given a prior θ parameter. From the combination of prior and new information it is obtained a posterior distribution of the characteristic value $P''(\theta|\hat{x})$, Eq. 3.

$$P''(\theta|\hat{x}) = \frac{P'(\hat{x}|\theta)P'(\theta)}{\sum(\hat{x}|\theta)P'(\theta)} \tag{3}$$

Model code (JCSS, 2006) provides valuable information about the uncertainty to consider and the most suitable probability density function (pdf) to adopt for each property. Although this methodology could provide reliable predictions regarding modulus of elasticity in bending it is still very inaccurate for the prediction of strength (Machado and Palma, 2011).

Two features always attract the attention of experts as possible strength-reduction factors – fissures and knots. The effect of knots on strength of structural timber members is generally difficult to assess since the existing models showed a significant level of uncertainty. Different approaches can be followed to obtain a reasonable prediction of weak zones resistance and to the reduction of clear wood resistance, eq. 4. ProTimber project will look upon the possibility of applying a model combination approach. This type of approach is expected to provide more reliable predictions of the effect of knots considering the onsite difficulties in the assessment of knots due to dust, poor lighting and lack of accessibility to all faces of the element.

$$X_{wz} = X_{cw} k_{knot} \tag{4}$$

Where:
X_{wz} – Resistance of weak zones

X_{cw} – Resistance of clear wood
k_{kont} – Knot-reduction effect.

Resistance update has also to consider aging effects and structural deterioration (including mechanical, physical and biological). Aging is a controversial issue and this paper will not cover this matter but a good review of the effects of aging can be found in Kránitz, *et al.* (2016). A safe k_{aging} factor of 0.9 can be used for a first analysis.

The second route mentioned before (information from past performance) relies on updating the resisting capacity of the structure by taking into consideration the global behaviour of the whole structure during past service performance. The history of performance is already considered in the appraisal of old buildings by application of some rules-of-thumb. For instance a suggestion is made that if a structure has endure without major damage a period of time of 100 years then repair of that structure is sufficient to ensure its safety and serviceability. Only if an increase of the level of actions or if a change of use is foreseen then a proper safety and serviceability assessment should be carried out (Ross, 2002). In the same line, recent Portuguese legislation allows that the works on existing structures are not oblige to comply with the actual requirements and should only ensure that no reduction of the structural safety and serviceability of the buildings occurs (it assumes that the initial conditions were sufficient to endure the building to the apply actions).

This type of evidence based on past performance is especially important to be considered when dealing with historic structures (with heritage value). Past performance information can be used to reformulate the resistance distribution function ($f_R(x)$), eq. 5 and fig. 3. If a structure survived a known combination of actions effect (AE) then a truncate resistance probability density function can be used and a lower probability of failure can be envisaged. This approach can be followed by using a proof-load test or from a satisfactory performance given a load-history (Val, et al. 2002).

$$f_R^*(x) = \frac{1}{1 - F_R\left(X_{AE}\right)} f_R(x)\,; x \geq X_{AE}\,; f_R^*(x) = 0\,;\; x < X_{AE} \qquad (5)$$

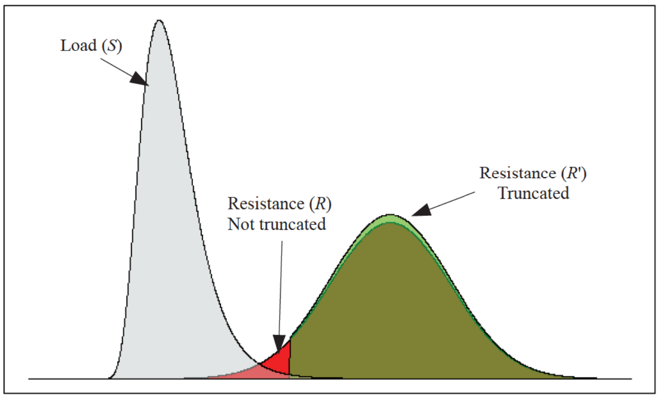


Figure 3. Load (gray), nontruncated resistance (red) and truncated resistance distribution curve (green) as a consequence of proof-load or past performance.

Although important and relevant the practical use of information from past performance is still under discussion namely in matters relating to how to assess load-history and the definition of the maximum load effect that timber structure suffered while in service.

Besides structural members also the behaviour of timber joints have to be look into more detailed during the second survey. Unfortunately insufficient research has been carried out in looking for assessment methods that could provide a reliable prediction of timber connections behaviour in-situ (Anthony, 2008). Nevertheless some result showed already that contrary to the general assumption some traditional timber joints can show some moment-rotation capacity (Crovella and Kyanka, 2011). As aforementioned guidelines or method to assess in-situ the performance of these joints is scarce. Carpentry and dowel-type connections will be studied within the ProTimber project. The capacity of this latter type of connections can be evaluated based on the design rules of Eurocode 5 and using indirect information as the geometry of the connection and material properties (e.g. dowel diameter, distances between fasteners and fasteners to the end of the element, wood density) (Köhler, 2007). Visual survey and NDT/SDT methods already exist for making the necessary measurements. Carpentry joints load capacity modelling can be done applying the component method (Branco and Descamps, 2015) or by using Bayesian regression modelling (Tannert and Haukaas, 2013).

2.2 *Time-variant effects*

Timber long-term mechanical performance is affected by many effects that are function of time and conditions of service. These time-variant effects result in a shift to the left of the probability density function of resistance and increasing the probability of failure (and consequent decreasing of the reliability index β), Figure 4.

Once more the complexity of timber turns these effects spread between biological, physical and mechanical causes. When inspection is carried out information is obtained about the actual state of the structural but as important as the actual situation is the capability to assess the past deterioration and predict the evolution in time of this deterioration. This information can be useful specially when dealing with historic constructions were some time could be necessary to ensure that decisions will not endanger its cultural value and therefore the adoption of existing conservation/repair/strengthening solutions can be delayed in time.

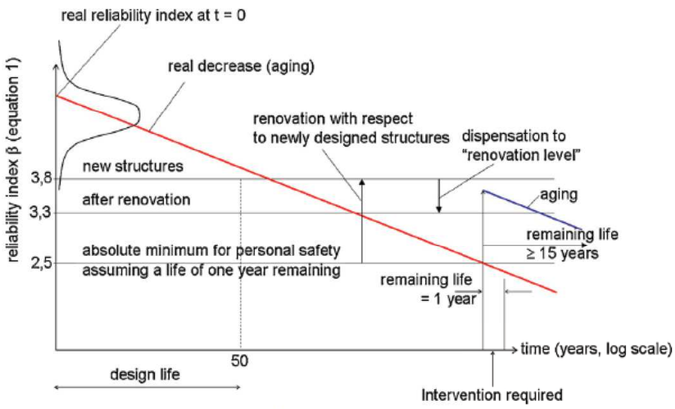
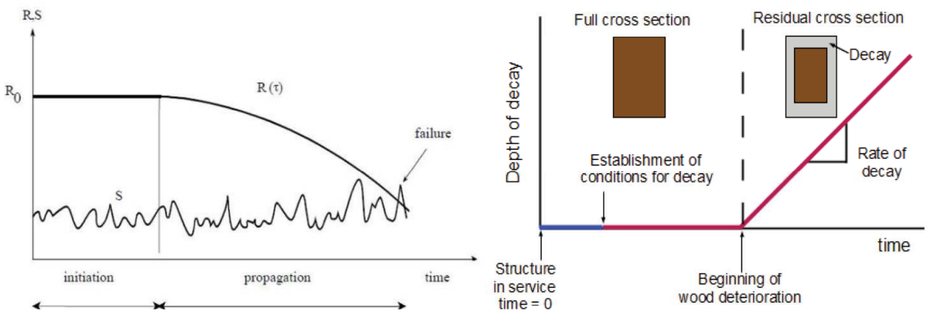


Figure 4. Different criterion to the assessment of structures according to NEN 8700 (Jorissen 2012).

Fissures are often the cause of many concerns about the safety of structures. The evaluation of their strength-reduction effect is generally based on a visual appraisal of its location and characteristics (namely length and depth). Areas identified as subject to significant perpendicular to the grain or shear stress are critical areas where the presence of fissures should be carefully appraised. Guidelines for the assessment of checks can follow the general limits provided in visual strength grading standards but if this is the case then most surveys would end up in costly repair works. Two issues of concern are: 1) how affected is the integrity of the member and connection by the presence of cracks; 2) is that crack stable or is prone of evolution with time (non-stationary process). More studies is necessary in this area and ProTimber project will studied the possibility of defining rules for the assessment of fissures onsite and how to assess their stability.

Biological damage can be represented as for fire as a loss of cross-section and this information can be used to obtain a picture of the safety of the structure at the present moment (Brites, *et al.* 2013). However this view do not provides information of the consequences of this deterioration with time (needed to plan maintenance and inspection works). Previous work by the research team of ProTimber proposed the use of general decay models as source of information for deterioration of the safety of a structure due to fungi deterioration, Figure 5 (Brites, *et al.* 2013).



a) b)

Figure 5. Damage model curve a) and b) resistance strength decay due to fungi action by reduction of the cross-section of structural members.

The usefulness of such procedure is dependent upon the calibration of several parameters (e.g. time to initiation given the proper conditions for the development of the fungi or the rate of decay given a particular set of conditions at the structure site). The definition of the residual cross section also raises the question about how to define the threshold between sound and incipient decayed wood. The ability of combine decay models with structural analysis results is crucial if the repair/strengthening works can not be done immediately and it is necessary to define a safe and reasonable timeframe for these interventions.

Mechanical damage is normally associated to the influence of stress level and duration of load (duration of load and creep) and is modelled by cumulative damage models (JCSS, 2006). Stochastic load models combined with damage models and probabilistic methods was used for the calibration of the load-duration (Sørense, *et al.* 2005).

In most situations the level of stress on timber members is well below 25% of the short-term ultimate load when only above 53% the load-duration effect takes place (Kránitz, et al 2016). The ratio σ_{sa}/σ_g (where: σ_{sa} is the stress predicted to the member from the structural analysis carried out; σ_g is the maximum stress level of the member considering the predicted resistance design value) provides information about the possibility of overstressed (above 35%) members where damage can have occurred. Possibly information on the occurrence of mechanical damage can be found in chemical modification of wood's polymer (cellulose). ProTimber will look upon this possibility using Near-Infrared spectroscopy hand-held equipment to assess possible alterations in the chemical composition of timber members and infer the presence of mechanical damage.

3 CONCLUSIONS

Considering timber's variability and the complexity of structural systems the expert's opinion (based strongly on visual inspection and grading) is still the foundation of timber structures assessment. However the maintenance of historic timber structures in service needs the ability to increase the reliability of expert's judgment. Probabilistic models allow to combine different types of information (qualitative and quantitative) and to handle with all the uncertainty connected to the prediction of timber structural members and connections behaviour.

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