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In-situ Assessment of Structural Timber: State-of-the-Art, Challenges and Future Directions

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Abstract Timber is one of the oldest structural materials and has been traditionally used in all parts of the world. Pressures on environmental sustainability lead to revitalization of timber as a modern, highly environmentally friendly and sustainable material. This new interest also sparks the attention of the research and engineering community in the structural applications involving timber. A number of techniques can be used to evaluate health, deterioration and extent of potential damage of historic structures and their components. Because timber is a natural, biodegradable, hygroscopic, and inhomogeneous material, its interaction with the environment presents challenges not normally encountered in materials typically studied by engineers. In addition, high variability of properties even within individual species makes it difficult to make inferences on properties of the investigated systems or even individual components. This requires a multidisciplinary approach and broad knowledge of disciplines spanning from biology and plant anatomy to mechanical properties and statistics. This paper will discuss some of the methods that can be deployed to evaluate historic timber and their drawbacks and limitations. Future directions and needs will be addressed in the last part of the presentation.

Keywords: Timber, in-situ evaluation, non-destructive method, semi-destructive method

Introduction

Wood is the only economically significant renewable structural material. Wood has been used for centuries in construction and proved to be highly durable if correct – and common sense – structural details are implemented. Wood compared to other significant structural materials such as masonry, concrete or steel has an advantage in low mass density and high strength/mass density ratio. This is illustrated in Figure 1. One point that needs to be made is the variability of the strength/mass density ratio (SM ratio) that is relatively high for wood but even a lower bound is significantly exceeding the one of concrete or steel. The SM ratio is an important measure of the material effectiveness and is especially important in seismic applications where inertia forces may control the design.

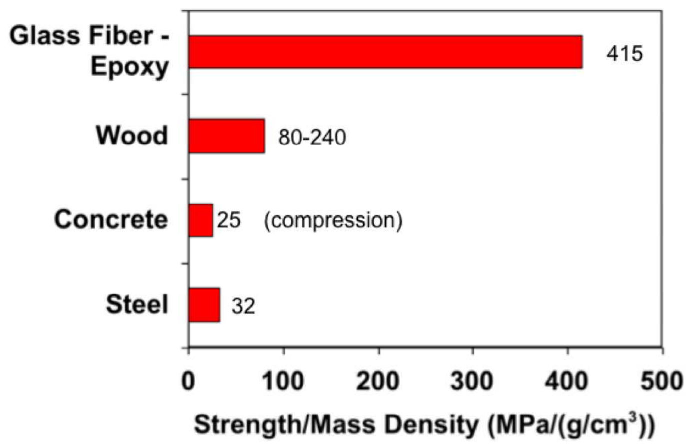


Figure 1: Strength/mass density ratios for glass fiber-epoxy, wood, concrete, and steel

Environmental performance is frequently measured in terms of embodied energy. Embodied energy represents total energy input associated with a material and includes the energy to manufacture, transport and install the material – *Table 1*.

Table 1: Embodied energy of major building materials (Ferguson et al 1996)

Material	*Fossil fuel energy (*MJ/kg*)*	*Fossil fuel energy (*MJ/m^3*)*
Rough sawn timber	1.5	750
Steel	35	288 000
Concrete	2	4 800
Aluminium	485	1 000 000

The difference in environmental impact between the materials is even more visible when equivalent CO_2 emissions are compared –*Table 2*. Note that CO_2 released in production of a one-ton of cement is between 750 and 1000 kg.

Table 2: Carbon released and stored in manufacture of major building materials (Ferguson et al 1996)

Material	*Carbon released (*kg/t*)*	*Carbon released (*kg/m^3*)*	*Carbon stored (*kg/m^3*)*
Rough sawn timber	30	15	250
Steel	700	5 320	0
Concrete	50	120	0
Aluminium	8 700	22 000	0

The disadvantage of timber is in its biodegradability and relatively large shrinkage and swelling coefficients in the direction perpendicular to grain. Most of the in-situ evaluation of historic timber is done via visual inspection and only in special cases use of more sophisticated methods is needed. Visual inspection usually discovers major defects, majority of which are connected with effects of moisture, fungi and insects. The corrective measures must include the identification of causes of deterioration and removing them. In most cases these causes are related to moisture accumulation, and removing moisture sources prevents further deterioration. Generally, in-situ evaluation of timber requires a set of skills not associated with a typical engineering education and significant knowledge of wood anatomy, wood-moisture relationship, wood decay mechanism, and wood insects are required.

Wood Deterioration

Generally, when wood is structurally protected it can theoretically have unlimited durability. The structural protection simply means keeping the material dry (see the comment on definition of dry below). This is achieved by capillary breaks between the foundation (or any wet substrate) and protection from any source of liquid water, usually rain (roof overhangs) or condensation. In historic structures, use of treated wood is unlikely and will not be discussed here. Contact between masonry (stone, rubble masonry, brick, etc.) always represents risks of elevated wood moisture contents due to the potential capillary water and condensation. If water penetration of wood cannot be avoided, a mechanism for drying (air access) must be provided. Air-dry wood will have moisture content between about 8% and 20% depending on the relative water vapor pressure (relative humidity of the air). These moisture levels are under most circumstances not conducive to wood fungus colonization and growth. The wood decaying fungi need three major components to grow: wood substrate, oxygen, and water. The only component that can be controlled is the presence (or absence) of water. Fungus almost always requires significant amount of water to be present, although some species (such as

Merulius Lacrymans) may colonize dry material. The somewhat vague definition of "dry wood" should be noted. Wood in structures will never have zero moisture content - it equilibrates with the surrounding environment. "Dry" is defined, for example as a wood moisture content at or below 19% (NDS 2005). Fungus may not always be detectable by the naked eye, especially in incipient stage. The hyphae can grow far from the visibly infested site and this must be investigated microscopically by a trained biologist or wood scientist. The amount of water needed for fungus to grow is well above the "wet" condition defined above and needs to be beyond the fiber saturation point (Fiber saturation point, FSP, is defined as moisture content where no liquid water is present in lumens and the cell walls are fully saturated. FSP is reached when relative humidity reaches close to 100% (air is fully saturated)). At that point, wood cell walls are fully saturated, but there is no water in lumens. Underwater historic structures or components will not be susceptible to fungus attack, due to the lack of oxygen that is displaced by liquid water in lumens. In salt water, however, wood-destroying organisms (marine borers) may be present even if there is a complete lack of oxygen.

Wood resistance to decay differs from specie to specie and the Wood Handbook (2002) categorizes wood species according to their resistance to decay as:

- Resistant or very resistant
- Moderately resistant
- Slightly or not resistant

For example, cedar or cypress are classified as resistant, Douglas fir and western larch as moderately resistant, and fir as not resistant. The document also classifies imported (from the US prospective) species. Precise definition of the above resistance levels is not, however, given. Insects such as carpenter beetles or termites usually require a certain amount of moisture to be present in wood, but some species can attack dry timber (Hylotrupes bajulus, for example). In such cases, more aggressive measures such as fumigation or application of insecticides are required. The loss of strength of even partially decayed wood can be significant and even incipient decay (fungus attack) compromises wood strength. At 1% of the weight loss (which is used as a measure of the decay level) the strength reduction between 6% and 50% was measured (toughness). When weight loss reached about 10%, strength reduction will be over 50% (Wood Handbook, 2002). These levels of decay cannot be, in most cases, indentified macroscopically (by naked eye). This means that microscopic analysis is always required to identify potential decay. It should be noted that fungus spores are almost always present in wood in dormant stage – most of the structural timber should be considered as permanently infested. Fungus activity can be stopped by simply drying the material, but the strength loss is permanent and level of fungus deterioration should be established microscopically.

In-situ Evaluation of Timber

Various methods have been used to evaluate timber in-situ. The use of a particular method depends on the questions that need to be answered. The following will focus on the material parameters (such as wood specie identification, age, level of degradation, strength estimates) and not on common structural aspect such as building geometry, orientation, age, soil conditions, surrounding buildings, etc., which, of course, are important parameters that need to be ascertained as well.

Methods of in-situ evaluation can be classified into three categories (Kasal and Anthony, 2004):

1. Destructive
2. Semi-destructive
3. Nondestructive

The destructive method will extract a member from a system and establish its properties via full-scale or reduced-scale (small-clear specimen) experiments. It will yield information about a particular member but inferences on properties of remaining members will be weak due to the variability between members. Semi-destructive methods use small specimens extracted from a structural member, such that their size is smaller than natural wood defects (such as knots), or significantly smaller than member dimensions. Thus the strength of the members is not affected – the

method is non-destructive with respect to the structural member and destructive with respect to extracted specimen. Due to the variability within a member (which at the same time can be viewed as a variability between samples), spatial distribution and number of samples taken will affect the reliability of prediction of desired parameters. Semi-destructive methods are local methods. This means that only properties of small areas are known and inferences must be made about the properties elsewhere. This is clearly a disadvantage in comparison to global methods that measure parameters over relatively large areas or even parameters of an entire section. The advantages of the semi-destructive methods lie in that mechanical or physical properties are measured directly and no correlations between a physical quantity measured and desired property are required (direct method). Nondestructive methods use relationship (usually correlation) between a nondestructive parameter (such as stress-wave velocity) and a destructive parameter (such as strength or modulus of elasticity – which by itself can be obtained nondestructively, but will require a member extraction – a destructive procedure). The level of information and required number of replications is illustrated in Figure 2.

The NDT methods require limited number of measurements and usually result in global parameters (parameters defining a property of a member as a whole), semi-destructive methods extract small specimens from a member and yield local parameters. In order to make inferences on member's properties, number of replications must be determined. Destructive tests extract the entire member (one replication) and yield complete information about the member in question. Of course, destructive tests are hardly possible in historic buildings. Individual test methods are summarized in the RILEM TC 215 state-of-the-art report (Kasal 2010). Extraction of small specimens is sometimes necessary to use methods such as microscopy for specie determination, dendrochronology, direct density measurements, etc. Many nondestructive methods require additional information that can only be obtained by semi-destructive methods, such as ultrasonic methods will require the knowledge of material density and moisture contents for a reasonable estimate of modulus of elasticity.

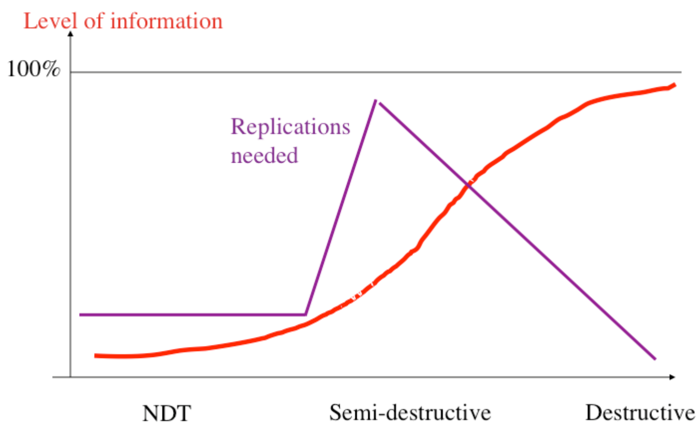


Figure 2: Relationship between evaluation technique and expected level of information

The Variability of Wood Properties is significant and must be considered in any evaluation of historic material. The sources of variability are numerous and result from variabilities between wood species, within the wood specie, between individual components in a structure, within an investigated component, and between specimens or measurements obtained from a single component. Understanding the sources of the variability is critical in designing the test strategy (experiment design) and result evaluation. Reliability of the data and conclusion are strongly affected by the material variability. In addition, used assessment techniques have their own inherent uncertainty (such as correlation between non-destructive and destructive parameters or test repeatability). *Table 4* lists typical ranges of coefficient of variation. From the table, it is clear that large differences between individual measurements can be expected. Knowing the expected variability and required risk of type one and type two errors, number of measurements can be estimated. This is a typical experiment design problem described well in the literature (Myers et al 2006).

Table 3: Methods for in-situ evaluation of timber

Method type	*Example of the method*
Destructive	Tests of the full-size members
Semi-destructive	Micro-tension tests Core drilling Screw withholding tests Penetration tests Resistance drilling Small specimen extraction
Non-destructive	Acoustic methods Ultrasonic methods Stress waves Radiography Visual observations Moisture measurements Ground penetrating radar

Table 4: Variability of properties of small-clear wood specimens (Burley, et al 2004)

Property	*Coefficient of variation (%)*
Bending strength	7-20
Modulus of elasticity in bending	9-23
Impact bending	25
Compression parallel to grain	8-29
Compression perpendicular to grain	28
Side hardness	20
Shear parallel to grain, shearing strength	14-22
Tension parallel to grain	25
Toughness	34

It should be noted that the reliability of each method would further weaken the power of prediction of investigated parameter(s), such as bending strength. For example, correlation between dynamic and static modulus of elasticity in bending can vary between 0.58 and 0.90 (r2 value) depending on the source. The correlation coefficient is higher for small-clear specimens and lower for large members (Kasal, 2010).

Current State-of-the-Art

The state-of-the-art in-situ evaluation of timber has been described in a RILEM TC 215 document "RILEM TC AST In situ assessment of timber State-of-the-art report" (Kasal, 2010). The evaluation of historic timber can be summarized in the following steps:

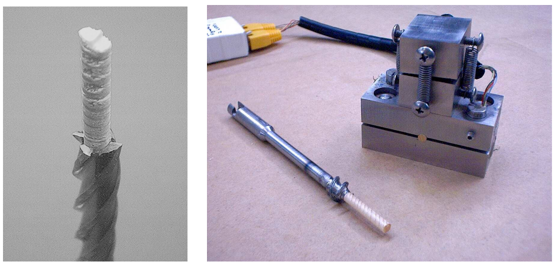
Visual evaluation
Specie identification
Moisture measurement
Evaluation of specific properties or parameters

Visual evaluation, specie identification, and moisture measurements are steps that are always present and must be used. Visual evaluation is used to identify overall health of the structure and wood members and it is the most important step in the process. Visual evaluation requires a well-trained professional with knowledge of wood science. Specie identification uses knowledge of

wood structure and anatomy and macroscopic and microscopic methods are usually used. Macroscopic methods (naked eye or magnifying glass) may not be conclusive and microscopic analysis is frequently required.

Moisture measurement is done via electrical moisture meters that use correlation between electrical conductivity and moisture contents. The measured values need to be calibrated for temperature and specie or a specie group, which implies that the specie identification needs to be done to obtain reasonable estimate of material moisture contents. The moisture meters measure the moisture contents (MC) locally and it can vary significantly from location to location. In addition to the MC measurement one may need to use psychrometric measurements to obtain the relative water vapor pressure (relative humidity of the air). The relative water vapor pressure fluctuates greatly with the temperature and amount of water being moved into or out of the environment. Long-term measurements (such as drum psychrometer) may be necessary to evaluate the parameters of surrounding environment. The methods to measure the MC or RH did not change greatly within the past decade. The State of the Art Report describing most of the classical and newly developed methods is available (Kasal 2010) and some of the methods will be discussed below.

Core Drilling. Core drilling has evolved from using an incremental borer used in forestry to determine the width of annual rings. Initially, core drilling was used to extract cores for visual inspection, density and moisture contents measurements. Low quality of cores extracted by the core drills originally designed for wet wood (growing trees) did not permit any type of reliable core tests. A number of technical challenges had to be resolved to obtain high quality cores that can be tested in compression (Kasal and Anthony 2004). New generation of equipment permits extraction of intact cores and testing them to obtain modulus of elasticity and strength in compression parallel to fibers. The method is local, requires planned specimen extraction (statistical experiment design), and laboratory equipment to test the cores. The method yields relatively reliable data. Since a small, clear specimen is extracted from a member, material properties such as density and moisture contents are also directly measured and specimens can be further used for microscopic and chemical analyses.



(a) (b)

Figure 3: Equipment to extract and test cores: (a) hollow drill bit with the core, and (b) core

Tension Microspecimens also described in Kasal and Anthony (2004) and Kasal (2010) require extracting a triangular specimen from the wood surface. The specimen has a side length of about 5 mm. The sample must be processed in a laboratory by reducing the cross-section in the area of strain measurement ("dog-bone" specimen) and attachment of end blocks to prevent failure in grips. This makes this test relatively time- consuming. The advantage is that modulus of elasticity and strength of the material is obtained directly with no correlation relationships required. As with the core method, specimens can be further used in establishing other physical or chemical properties. The method requires specialized equipment for in-situ extraction and laboratory equipment for tensile tests. The test equipment is shown in Fig. 4.

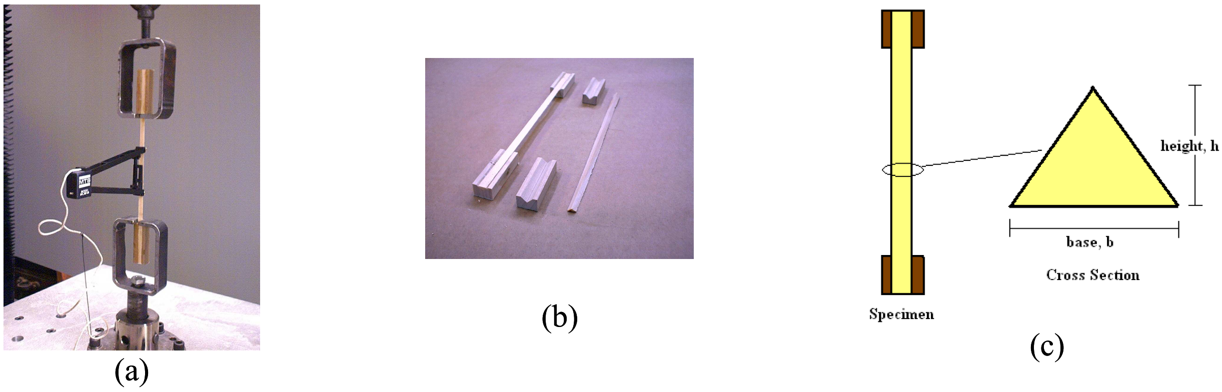


Figure 4: Test setup, specimen and schematic of the tension micro-specimen: (a) test fixture with the extensometer, (b) test specimens, and (c) schematic of the extracted specimen

Resistance Drilling. Resistance drilling is based on movement of a standard drill bit into a material. At a constant cutting speed (say per cutting edge of a drill bit or per revolution) the energy required for the drill to progress at a constant feed speed will be a function of the material's resistance. The method is therefore indirect and relative energy (drop or increase) is used to make inferences on internal defects of the member (such as voids or decay). The method can be relatively sensitive and individual growth rings can be detected. In structural timber, which is mostly dry, the small-diameter (about 1,5 mm) long (up to 400 mm or more) needle tends to follow the curvature of the growth rings (if present) thus resulting in errors. This can be avoided by larger needle diameter (increasing the stiffness of the drill bit). The position of the tip of the drill bit is recorded and this permits exact detection of a start and end of the internal feature. Clearly, resistance drilling is a one-dimensional mapping of an internal feature and combination with other methods (such as radiography) will increase its power. As mentioned above, visual inspection is always necessary and is particularly useful in the application of resistance drilling. Resistance drilling under angle permits investigated locations otherwise impossible or difficult to inspect such as beam pockets. The record shown in Figure 5 shows the position of the drill bit tip versus energy required for the tip to progress. The horizontal line with low level indicates void in the cross section.

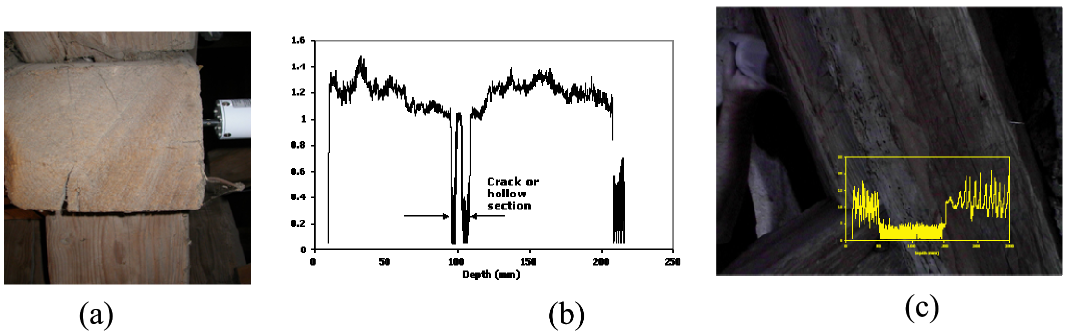


Figure 5: Resistance drilling, typical diagram showing the drill bit tip position (depth) and relative energy and result interpretation. (a) equipment, (b) output example, and (c) mapping the output with the tested object

Radiography. Radiography uses penetrating radiation to measure the intensities passing through the object. The intensity of a passing beam will be affected by the absorption rate of the material. The total absorption is based on the material density and its thickness. Wood is an excellent candidate for the application of radiography, due to its low absorption of radiation. Thus, low-level sources can be used to investigate internal structure of in-situ members. The radiation sources can be electrons, neutrons, gamma rays and X-rays. For practical applications, gamma or x-rays are used. No external power source is required for the gamma rays, but a permanent one is used (unstable radioactive isotopes). The permanent source requires special containers, and this makes the gamma rays less

useful from the safety viewpoint. The x-rays are emitted when high-speed electrons impact matter. With the advent of portable, battery-operated sources, the x-ray systems have been almost exclusively used for in-situ work. X-ray sensitivity and accuracy depends on the number of parameters associated with the emitter (x-rays source) and receiver. Real-time systems (image is immediately displayed) or systems with sensitive plates and a scanner can be used. Generally, systems with plates and scanner offer more resolution, but for most in-situ work, both systems are acceptable. The plates have advantage of their small thickness (less than a millimeter) and can be deployed in areas with limited access. Figure 6 shows the schematic of the radiographic method.

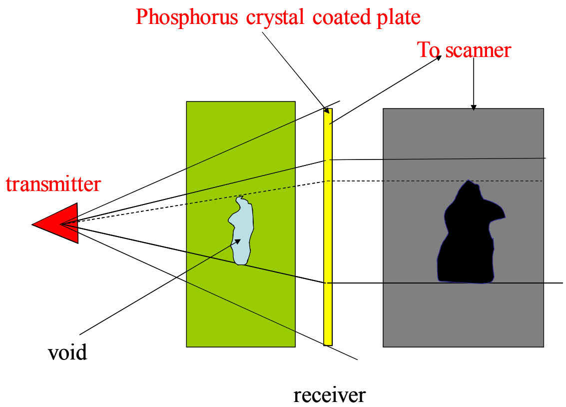


Figure 6: Schematic of the radiographic equipment

One of the disadvantages of this method is that one must have access to the investigated object from two opposite sides (source-object-receiver). The three-dimensional structure is collapsed into a two dimensional image and this may make the image interpretation difficult. Again, combination with visual inspection is necessary. Combination with resistance drilling, for example, will allow mapping the extent of the void or internal damage. Different absorption rates and low attenuation of wood facilitates excellent resolution in application to timber. This is demonstrated in Figure 7. Clearly, lower energy rates will result in higher resolution (attenuation coefficients depend on the energy levels).

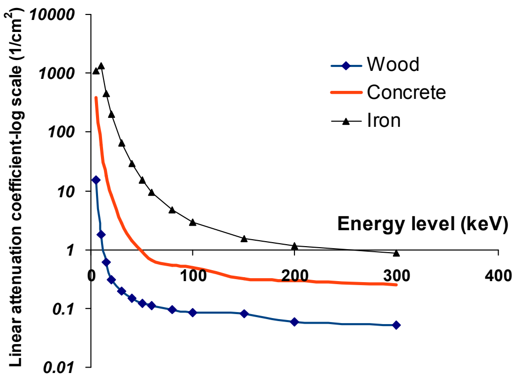


Figure 7: Linear attenuation (absorption) coefficient for wood, concrete and steel (Kasal, 2010) as a function of energy level

Fig.8 shows typical radiographic images of wood with voids and mechanical connections. In Fig.8, the annual rings are clearly visible. Such sensitivity can be achieved because of the low mass attenuation of wood. This permits using low energy levels that result in relatively high resolution. Interpretation of radiographic images is challenging because all features or objects are collapsed into a single two dimensional picture. Most recently, quantitative x-ray imaging has been introduced, which allows extracting deformations and dimensions (Adams and Kasal 2010). A number of challenges need to be overcome before the technique can be effective in quantitative assessment.

They include resolution of imaging plates, separation of internal features, and errors associated with the angle between the x-rays and the plane of deformation.

Figure 8: Typical radiographs of investigated historic wood

Stress Waves and Acoustic Methods Application of stress waves in nondestructive investigation of wood members is quite common and stress waves have been used for some time. The most common measured parameters are time of flight or wave velocity but attenuation and frequency spectrum analyses can be used to extract additional information. The method can be used to detect interior defects or deterioration of wood and is used to make inferences on mechanical properties. Waves of different frequencies can be used ranging from audible range to frequencies exceeding 20 kHz (ultrasonic waves). The stress wave methods are useful in relative comparisons between and within the wood members (low-velocity regions versus higher-velocity regions). In order to estimate the dynamic modulus of elasticity, the density of the material must be known. This requires some kind of a sampling extraction, and the results will always be affected by various variabilities discussed above. Furthermore, the static modulus of elasticity is related to dynamic one via correlation with correlation coefficients (r2) reported between 0.58 and 0.96. This weakens the predictive power of the stress-wave methods.

Ground penetrating radar. Ground penetrating radar (GPR) is an application using electromagnetic waves. GPR can be used for detection, distance measurement, defects and anomaly localization, and characterization of dielectric materials such as soil, concrete, masonry and wood. The frequency range of the technique varies between 100 MHz to few GHz. Since the dielectric constant of wood depends, among other factors, on wood density and moisture contents (given constant temperature and frequency), these two quantities must be measured or estimated and their variation will affect the GPR measurements. Reflective properties of interfaces are utilized in thickness measurements and detection of internal defects. Two dimensional images can be constructed by superimposing the motion of an antenna and the detected reflected waves – Figure 9.

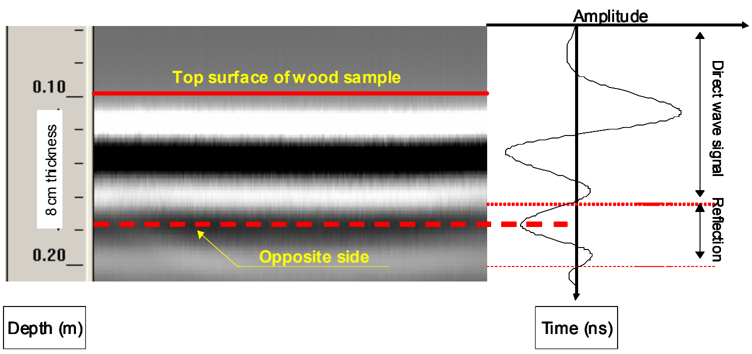


Figure 9: GPR profile of a timber beam (Sbartai 2010, in Kasal 2010)

The GPR has been used to detect voids and cracks in beams, timber bridges and other structures. Potential enhancement of the technique will involve GPR tomography where a 3-dimensional representation of an object can be constructed. This requires, however, access to the surfaces of an investigate timber, which may not always be possible.

Conclusions

Number of other methods for in-situ evaluation of timber is used (see Kasal 2010) but none of the method gives complete information about shape, health and mechanical properties of the timber. All methods, especially nondestructive, are contaminated by the natural variability of wood. From the author's experience, it appears that a visual inspection is the most practical and powerful tool despite significant progress in the NDT technology. Only exceptionally, technologies such as semi destructive techniques or GPR or radiography are necessary. Future developments will include enhancement of existing techniques to reconstruct three-dimensional images of the investigated materials (GPR, x-ray tomography, etc), rapid chemical analyses, which can detect presence of biodeterioration, and application of multiple techniques with multiple data array processing. The combination of mutually independent techniques can significantly enhance the predictive power that will far exceed the predictive power of any isolated method. This will, however, require a development of models for using multiple predictors.

Literature References

[1] Adams, A, and Kasal, B (2010). "*Non-Contact Strain Measurement using Radiography and Digital Image Processing.*" Experimental Techniques. The Society for Experimental Mechanics. Blackwell Publishing, Inc. (in print).

[2] Burley, J, Evans J, and Younquist J (Editors) (2004). "*Mechanical properties of wood.*" Encyclopedia of Forest Science. Elsevier Publishing Co., Oxford, England. ISBN 0121451207. 2000 p

[3] Ferguson, I, LaFontaine, B, Vinden, P, Bren, L, Hateley, R, and Hermesec R (1996). "*Environmental Properties of Timber.*" Research paper commissioned by the Forest and Wood Products Research and Development Corporation. Victoria, Australia.

[4] Kasal, B (Editor) (2010). "State-of-the-art in in-situ assessment of timber." RILEM TC AST 215 Special Publication. Springer Verlag/RILEM Paris (in print)

[5] Kasal, B, and Anthony R (2004). "Advances in in situ evaluation of timber structures." *Progress in Structural Engineering and Materials.* John Villey & Sons Ltd. London. UK. 6(2), 94-103.

[6] Myers, R H, Walpole, R E, and Myers, S L (2006). "*Probability & Statistics for Engineers & Scientists (8th Edition).*" Prentice Hall.

[7] *National Design Specifications for Wood Construction (NDS)®.* 2005 Edition. American Forest and Paper Association, Washington, DC.

[8] Wood Handbook (2002). "Wood as an Engineering Material." *Information on engineering with wood, properties of wood and designing with wood.* September 28, 2002. Forest Products Laboratory. 1999. Wood handbook--Wood as an engineering material. Gen. Tech. Rep. FPL-GTR-113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 463.