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Master in Construction Research, Technology and Management in Europe

Final Dissertation

Non-destructive diagnostics for timber structures in historic buildings:
Investigation methods and testing tools

Diagnóstico no destructivo de estructuras de madera en edificios históricos: métodos de investigación y herramientas de prueba

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Abstract

Non-destructive testing is a relatively new field in construction and shows great potential for in-situ testing. Especially for historic structures where no alterations, interventions or damages due to tests are desirable, this form of assessment is ideal. Problematic is that only very little regulations in form of standards and codes exist in this field that would harmonize not only the assessment procedure but also the procedure of the individual techniques.

This report performed a theoretical research study to investigate the different techniques and evaluate their potential, limitations as well as their practical implementation so far. The reviewed techniques include visual inspection, moisture measurement, ultrasonic measurements, radioscopy, thermography, ground penetrating radar and the semi-destructive Resistograph (resistance drilling). Following the theoretical part of the study, available codes, standards and guidelines concerning this field of work were critically analyzed. Among these standards were the Euro Code 5, ISO 13822, SIA 269 and UNI 11119. The Italian standard UNI 11119 was thereby the only one available in detail and used for the development of a guideline/best practice consisting of non-destructive techniques that would satisfy the requirements set by the standard. It was concluded that the separate techniques are best used in combination as one alone is not sufficient enough to fulfil the standard's requirements. A laboratory investigation using some of the reviewed techniques was performed as well, confirming the benefits of combining techniques as salience form visual inspection was confirmed by resistance drilling and ultrasonic through-transmission for instance. The resulting laboratory report can be found in the annex.

A conclusion was drawn that the benefits of non-destructive assessments are plentiful as it allows investigating structures without disturbing them, using non-destructive techniques in situ. This is crucial for historical structures as it is possible to differentiate between sound and damaged structural members, which decreases the amount of interventions significantly, preserving cultural heritage.

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Table of Contents

Final Dissertation 1
1. Introduction 1
1.1 Background 1
1.2 Aim and Objectives 2
1.3 Limitations 2
2. Construction Material Wood 3
2.1 General Information 3
2.1.1 Structure 3
2.1.2 Properties 4
2.1.3 Decay 2
2.2 Need for Assessment of Structures 3
3. State of the Art of Assessment Techniques 5
3.1 Non-Destructive Techniques 5
3.1.1 Visual Inspection 5
3.1.2 Moisture Content Estimation 6
3.1.3 Ultrasonic Method 7
3.1.4 Radar Scanning 9
3.1.5 Thermography 11
3.1.6 Radiography 12
3.2 Semi-Destructive Techniques 14
3.2.1 Resistance Drilling (Resistograph) 14
3.3 Case Studies and Combination of Methods 15
4. Available Standards and Guidelines 17
4.1.1 ISO 13822 (2012) 17
4.1.2 Eurocode 5 (EC 5/ EN 1995) 18
4.2 National Standards 19
4.2.1 UNI 11119: 2004 19
4.2.2 SIA 269 20
4.3 Available Guidelines in Accordance with Standards 22
5. Guideline for Assessment 24
5.1 Preliminary Assessment 24
5.1.1 Input 24
5.1.2 Phase 24
5.1.3 Expected Results 24

5.2 Species Identification 24
5.2.1 Input 24
5.2.2 Phase 24
5.2.3 Expected Results 25
5.3 Moisture Content 25
5.3.1 Input 25
5.3.2 Phase 25
5.3.3 Expected Results 26
5.4 Structural Member Inspection 27
5.4.1 Input 27
5.4.2 Phase 28
5.4.3 Expected Results 32
5.5 Additional Useful Applications 33
5.6 Procedure Recommendations 34
5.6.1 Resistance Method 34
5.6.2 Ultrasonic Testing 34
5.6.3 Radioscopy 35
5.6.4 Thermography 36
5.6.5 Radar Scanning 36
5.6.6 Resistance Drilling (Resistograph) 37
6. Use of NDT in Laboratory 38
7. Conclusions and Future Research 39
8. Bibliography 41
Appendix 45

List of Figures

Figure 1 – Rotten Timber Structure with Safety Propping (Cruz, et al., 2015). 1
Figure 2 – Three Sectional Planes of Wood (Niemz, 2006). 3
Figure 3 - Orientation of Fibers (Pinto, 2008). 1
Figure 4 - Types of Cracks (Schäffler, Bruy, & Schelling, 1996). 1
Figure 5 - Wood-destroying Fungi (Suttner, 2002). 3
Figure 6 - Example of Crack Measuring; Example of Crack Mapping (Dietsch, Philipp, & Heinrich, 2011). 5
Figure 7 - Schematic of Resistance Method with Insulated and Non-Insulated Electrodes (Dietsch, Franke, Gamper, Franke, & Winter, 2015). 6
Figure 8 - Schematic of the Through-transmission Method (Baron, 2009). 7
Figure 9 - Schematic of the Pulse-echo Method (Baron, 2009). 8
Figure 10 - Projection Planes for Ultrasonic Scans (Riggio, 2013). 8

Figure 11 - Operational Principal of Ground Penetrating Surface (De Fino & Fatiguso, 2016).............. 9
Figure 12 – Principle of Active Thermography (BAM, 2004).. 11
Figure 13 – Thermal Contrast Image (left) from Impulse Thermography and Phase Image (right) from Pulse-phase Thermography (BAM, 2004). 12
Figure 14 – Schematic of an X-ray Scan Setup (top) and X-ray Equipment (bottom) (Lechner, 2013). 13
Figure 15 – Experimental Setup of X-ray Scanning (left) and Captured Image of a Wooden Beam with Metallic Elements Inside (right) (Riggio, et al., 2013). 13
Figure 16 - Resistance Drilling Equipment; Result of a Resistance Drill Visualized as a Graph with Penetration Depth and Encountered Resistance (Riggio, 2013)... 14
Figure 17 - Flowchart for the General Assessment of Existing Structures (ISO, 2010). 18
Figure 18 – Decision Path for Assessing Existing Structures (SIA 269, 2009. 21
Figure 19 - Steps Required for the Assessment and Planning of Interventions in Historic Timber Structures (Cruz, et al., 2015)... 23
Figure 20 - Decision Path for the Identification of the Used Species... 25
Figure 21 – Exemplary Depiction of Different Moisture Causes. 26
Figure 22 - Decision Path for the Determination of Moisture Content. 27
Figure 23 – Location of Beams Found Through the Use of Ground Penetrating Radar (Hasenstab, 2006)... 28
Figure 24 - Decision Path for the Inspection of Structural Members.. 32

List of Tables

Table 1 - Overview of Common European Trees (Knigge & Schulz , 1966)... 5
Table 2 - Classification Rules for Wooden Structural Elements in Operation (UNI, 2004). 19
Table 3 - Maximum Stresses According to Species and Category of Wooden Elements in Operation (UNI, 2004). 20
Table 4 - Techniques for Localization and Geometry of Hidden/Plastered Elements. 29
Table 5 – Techniques for Analysis of Interior Characteristics. 31

1. Introduction

1.1 Background

Being a renewable and steadily available material, wood is and has been used frequently as a construction material. Especially older or historic buildings often contain a wooden structure. However, being an organic material, it is exposed to weathering, decay and deterioration in general over time which influences its structural behavior and can result in safety risks as can be seen in the figure below. For structures of cultural heritage these threats are particularly dangerous since alteration or replacements of original parts are often undesirable. Therefore, structural elements have to be investigated in a non-destructive fashion in order to preserve them. Traditional assessment methods often included destructive measures through sample taking and tests such as flexural, tensile or compression (Lechner, 2013). For a long time, non-destructive testing was only possible through visual inspection and solely concerned surface characteristics. However, with modern equipment it is possible to assess structures and their members in a fully non-destructive fashion and with reliable estimations on material quality and overall stability.

Figure 1 – Rotten Timber Structure with Safety Propping (Cruz, et al., 2015).

Non-destructive techniques have therefore been used in many studies (Kasal & Tannert, 2010; Lechner, 2013; Riggio, 2013) to assess timber structures and include methods that allow to examine the interior structure of elements without damaging them in any way. Additionally, modern equipment offers to inspect structures in-situ as the gear is very handy and sometimes requires just one-sided access to a structural element. Among these are enhanced visual inspection tools such as ultrasonic measurements, radar scans, radioscopy or thermography. But not only non-destructive techniques have been enhanced, and so semi-destructive methods such as the Resistograph (resistance drilling) have become a powerful tool for assessments, leaving only minor damages, yet offering vital information on material properties and dimensions.

Although, older structures have a much higher need for assessments, newly constructed buildings also require frequent assessments. A lack of maintenance, poor workmanship or external causes can provide a target for biological decay and other strength diminishing influences (Lechner, 2013). Of course, the first concern for an assessment is focused on the safety and stability of the structure, yet, non-destructive testing also offers environmental and financial benefits. By not requiring sample-taking and being able to distinguish between damaged and sound structural members, thus lowering the amount of interventions, less material and construction work are needed (Morales Conde, Rodriguez Linan, & Rubio de Hita, 2014). Additionally, non-destructive techniques offer early detection of harmful influences and can therefore be used as a periodical check to prevent future repairs and interventions.

While there are enough reasons for an establishment of non-destructive techniques as an assessment method through harmonized standards and procedures, only very few of those can be found, which was already criticized by several authors (Tannert , Kasal, & Anthony, 2010; Rug, 2014; Löwenmark, 2009). Few national standards from Italy and Switzerland are available but no international standard can be found that is comparable to the national ones. With the EC 5 and the ISO 13822 two codes exist that deal with the assessment of existing structures, however, it is held too general and not material specific. Additionally, only some standards can be found that regulate the individual non-destructive techniques and their procedure. Hence, the call is great for the development of further standards covering non-destructive assessments of wooden constructions and the correlated procedures, in order to establish this beneficial form of in-situ testing as an established assessment method.

Therefore, the focus of this study is laid upon the few existing standards and non-destructive diagnostics that can be used to satisfy the standard requirements and develop a recommendation based on the suitability of the different techniques.

1.2 Aim and Objectives

This study is focused on the assessment of historical timber structures by using non-destructive techniques. The aim thereby is to investigate limits and potentials of non-destructive testing methods and develop a guideline/best practice, including the most useful methods that can be applied to satisfy the requirements of an assessment of a historical wooden structure.

The objectives expected to help accomplish this aim are:

- To perform a state of the art investigation on existing visual inspection and testing methods, describing their procedures, applications and limitations.
- To assess acquisition protocols and elaboration routines of non-destructive techniques for timber structures by laboratory activities.
- To develop a guideline/best practice based on the state of the art investigation that can be applied universally for historical timber structures.

1.3 Limitations

In order to realize the aim of this study the scope needed to be narrow, therefore this study includes the following limitations:

- An in-situ assessment or case study using non-destructive techniques and including a structural analysis and diagnostic report was not performed.
- Not all reviewed techniques were performed in laboratory.
- Intervention work or the design of it was not part of this study.
- Assessment criteria outside the scope of the used codes and standards was not regarded.

2. Construction Material Wood

2.1 General Information

Wood has been used as a construction material within living memory due to its accessibility and easy workability. It is a unique, natural and re-growing material that is highly favored in construction as it has a relatively low deadweight with reference to its high strength (Hasenstab, 2006). Especially nowadays, where sustainability plays a major role in the construction industry, timber has been rediscovered as it requires low energy in production, has a low thermo-conductivity which benefits isolation and does not produce any waste as all side products are utilized.

2.1.1 Structure

The structure of wood varies depending on the species yet the general composition stays the same and, according to Niemz (2006) can be divided into the following three sectional planes, as shown in the figure below.

- Cross (Axial) Section: The section in grain direction. A usually circular profile with the oldest part, the pith, in the center. The separate growth rings surround the pith and are visual to the bare eye. The rings are disrupted by medullary rays, growing from the inside to the outside that are responsible for the radial nutrient supply of the tree.

- Radial Section: The section orthogonal to the grain direction. It shows the crossover of the axial and radial section where the medullary rays proceed in horizontal direction.

- Tangential Section: The section, parallel to the grain direction. Here, growth rings are harder to detect and the cross section of the medullary rays can be seen.

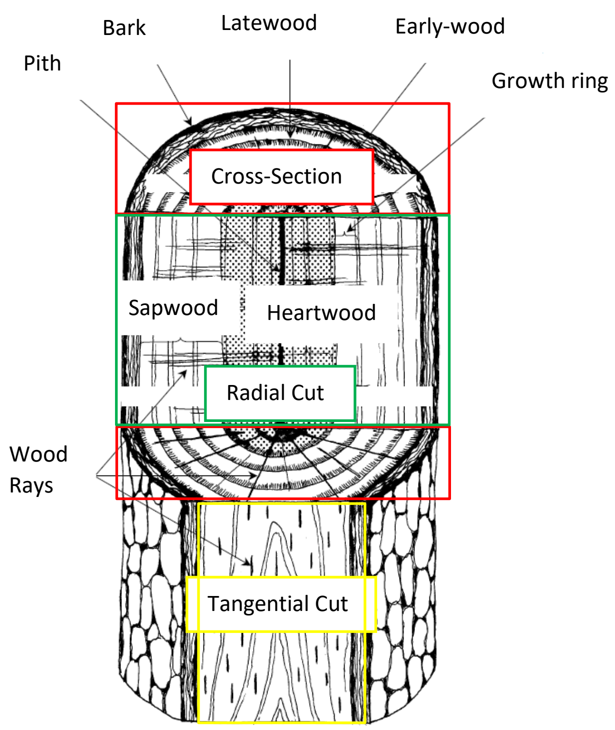


Figure 2 – Three Sectional Planes of Wood (Niemz, 2006).

The cross section of a tree can be divided into three main categories; bark, wood and cambium. The bark represents the outer part of a tree and can be divided into outer and inner bark. The outer bark protects the external damage whereas the inner bark stores and vertically transports nutrients through the tree.

Similar, the wood of a tree can be divided into the outer sapwood and the inner heartwood. In general, the main function of wood is to bear the tree as well as store and distribute nutrients (Pinto, 2008). Thereby, the sapwood which consists of dead tissue and water-bearing medullary rays is responsible for the transportation and storage of nutrients. The heartwood on the other hand contains the pith that due to the storage of secondary plant compounds has a higher density and strength than the sapwood. Additionally, the older heartwood often has a darker color and sometimes shows a higher resistance towards fungi as well as insects (Niemz, 1993).

The last category is the cambium which is located inside of the inner bark and outside of the sapwood. Cambium is the growth layer in a tree and through cell division creates new cells that will form a new growth ring (Niemz, 2006). Due to the different climate conditions throughout a year these rings are formed. At the beginning of the vegetation period, early-wood rings are produced with large cells and thin walls. Whereas at the end of the period, latewood rings are produced, where the cell dimension is smaller but the walls thicker (Pinto, 2008). The field of dendrochronology is focused on growth rings and is able to determine age as well as climate and environmental conditions the tree went through (Hasenstab, 2006). However, in regions without distinct seasons, no growth rings are formed as the tree grows constantly (Niemz, 2006).

2.1.2 Properties

The main properties of timber that influence its mechanical strength are density and moisture content. Additional influence is due to the orientation of fibers and inhomogeneities such as knots.

Density

Density is thereby one of the most important properties as it influences almost all other characteristics such as strength or thermos-conductivity. According to Niemz (1993) the compression, tension and bending strength are proportional to the woods density which is also taken into account in the German standard DIN 1052. Since timber is a porous material, its density varies sometimes largely, not only between species but within the same species as well (Hasenstab, 2006). The variety of density is contingent upon a tree’s genetics and influenced by climate and environmental conditions (Niemz, 2006). The table below shows density values of common European trees where the differences of density within the same species can be seen.

Wood Species	Dry Density [Kg/m³] $\bar{x}$	Limit Values [Kg/m³]		Bulk Density [Kg/m³] $\bar{x}$
		Xmin	Xmax	
Balsa	130	70	230	121
Fir	370	310	460	339
Spruce	420	280	610	332
Poplar	370	270	650	377
Douglas Fir	470	360	630	412
Pine	490	300	860	431
Larch	550	400	820	487
Maple	590	480	750	522
Elm	640	440	820	556
Ash	650	410	820	564
Oak	640	380	900	561
Guaiacum	1230	1200	1320	1045
European Beech	660	540	840	554

Table 1 - Overview of Common European Trees (Knigge & Schulz , 1966).

Moisture Content

Although, density is influencing other timber properties largely, it is itself altered by the moisture content. The reason for this is that wood is a hygroscopic material, meaning it absorbs water from its surroundings and stores it (Niemz, 1993). The more water gets absorbed, the more the strength and sonic speed decreases (Hasenstab, 2006). Especially the last parameter is vital to non-destructive assessment methods such as the ultra-sonic technique, which is described in section 3.1.3.

The moisture content of living trees varies from 25% to over 250% and since the distribution takes place within the sapwood, it is usually moister than the heartwood (Pinto, 2008). For wood elements from European trees, the moisture content is normally 12% under a constant, standard atmosphere of 20°C and 25% relative air humidity (Hasenstab, 2006).

Orientation of Fibers

Another major influence on the mechanical properties, especially strength, of wooden elements is the orientation of fibers. Besides growing in height, trees grow diametrically with its longitudinal axis parallel to the grain direction, making it an anisotropic material (Niemz, 2006). This means its physical and mechanical behavior is highly direction-dependent. Thereby, the differences between the radial axis (perpendicular to growth rings) and the tangential axis (perpendicular to grain direction) is rather low when compared to their differences towards the longitudinal axis (parallel to grain direction) (Pinto, 2008)

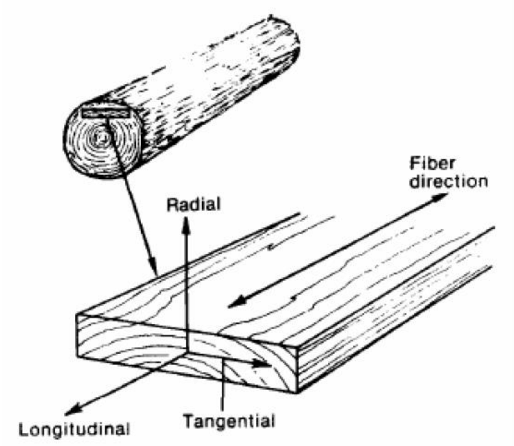


Figure 3 - Orientation of Fibers (Pinto, 2008).

Inhomogeneities

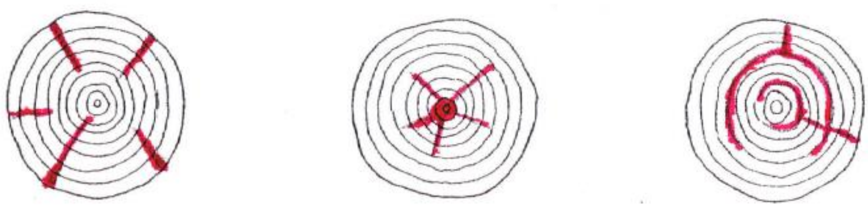
Almost all timber elements contain natural defects such as branches, cracks or growth defects.

According to Schäffler (1996) there are three types of cracks:

- Shrinkage cracks (Image 5a)
  These occur due to moisture descents in combination with different shrinkage behaviors during the drying of the wood from the outside to the inside. As a result, tensional forces are acting on the surface and cause cracks once the tensional strength is exceeded.

- Core cracks (Image 5b)
  Occur shortly after the cutting down of a tree and yawn from the core to the outside.

- Ring cracks (Image 5c)
  Are caused by ring- or wound rotting or by the different dimensions of the growth rings. They run circular along the growth rings.



a) Shrinkage cracks b) Core cracks c) Ring cracks

Figure 4 - Types of Cracks (Schäffler, Bruy, & Schelling, 1996).

Other types of cracks worth mentioning however rarely occurring are due to heavy external damage like frost or lightning strike. For constructional timber, the "Information Service Wood" dealt with cracks and whether or not these are tolerable (Frech & Waldachtal, 1987). According to it, core and ring cracks are not tolerable under any circumstances and elements containing these have to be replaced.

Branches

Although, branches are removed when trees are cut down, they still have a large influence and appear as knots in sawn timber elements. Branches occur during the normal growth and deflect the fibers into a lateral direction. As a result, the strength of the wood decreases when a knot is present as the direction of grains is changed (Pinto, 2008). Additionally, lose branches and branch knots can be seen as holes that cause a reduction in the cross section of the element (Niemz, 2006).

Growth Defects

Growth defects are understood as the deviation of wood from the normal, straight and symmetric growth of a trunk for example when the trunk is growing crooked, twisted or decreasing in diameter with increasing height (Simpson & TenWolde, 1999).

2.1.3 Decay

Wood is an organic material and therefore suffers not only from over time occurring mechanical decay due to its load-bearing but also from biological decay through insects or fungi. While mechanical decay can often be seen by the bare eye as it appears mostly on the surface (Niemz, 2006), biological decay is frequently located within a timber element and therefore not only harder to detect but also more dangerous as it decreases its strength (Pinto, 2008). All decay causes general or local loss of stability and causes structural failure in the worst case.

Mechanical Decay

As stated above, mechanical decay originates over time due to the load that a timber element has to carry. Thereby, the decay can occur not only on the element itself but also on connections/joints and results in different shapes and types of cracks, ruptures, deformations, etc. (Simpson & TenWolde, 1999). Depending on the type of flaw, the acting stress responsible can be determined as well as the presence of natural deterioration. In sound wood, flaws will appear frayed, irregular and progressive while flaws in deteriorated wood will appear sharp, straight and instantaneous (Pinto, 2008). Besides the wooden members of a structure, also metallic elements that are used mostly for connections can experience corrosion and affect the whole stability of the structure.

Fungi Decay

Wood-destroying fungi infects wood through airborne spores and is not preventable constructional-wise. However, certain parameters like the presence of wood or wood-related materials and a moisture content of at least 20% need to be fulfilled for fungi to grow (Hasenstab, 2006). The most dangerous part about fungi decay is that the material strength can decrease within a short amount of time and without warnings in form of cracks or ruptures (Suttner, 2002). According to their pattern of damage, fungi can be divided into color-changing fungi and destructive fungi as shown in the diagram below.

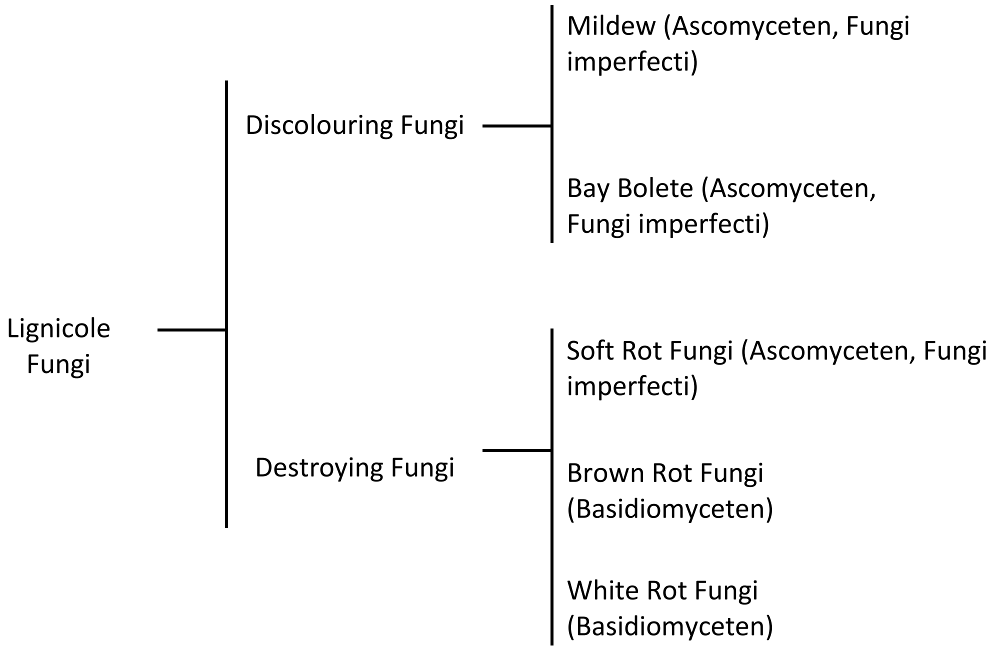


Figure 5 - Wood-destroying Fungi (Suttner, 2002).

Thereby, the destructive fungi are, as the name indicates, the more dangerous ones as they generally destroy cellulose and lignin which causes a reduction of density and strength (Niemz, 2006). Problematic when dealing with fungi decay is that although the strength decreases heavily it can easily stay undetected. Therefore, codes and standards like for example the German DIN 68800 requires removal up to 1,5m away from the visible damage (Hasenstab, 2006).

Insect Decay

Decay related to insects mostly occurs on the surface of a timber element and is caused by insect larva that perforates the wood, feeding on the cellulose and leaving tunnels with a diameter of up to 7mm behind (Hasenstab, 2006). Most insects prefer timber with a relatively high moisture content, found especially in "freshly felled logs or wet decaying timber" (Pinto, 2008, p. 28). However, according to Kempe (1999) also dried and built-in wood can be affected. Particularly dangerous are insects that live within the wood over years and grow inside of it undetected. Equally dangerous is, when insect decay is combined with fungi decay, as the presence of fungi causes even the heartwood to be eatable by insects (Niemz, 2006).

2.2 Need for Assessment of Structures

Many historic buildings rest upon timber structures that face deterioration and other defects over time as described above. Furthermore, historic structures were often built rather by improvisation than by following a plan (Löwenmark, 2009). Additionally, with wood becoming more popular as a construction material due to its sustainability, workability and availability, reliable assessments and estimations about wooden structures are required (Krause, et al., High-precision structure recognition of wooden construction elements with 3D ultrasonic (Hochgenaue Strukturerkennung von Holzbauteilen mit 3D-Ultraschall), 2013). Thereby, non-destructive techniques are highly favorable as they do not damage the structure, making it possible to assess a structure without taking out or replacing members. This especially benefits historic structures as original parts are conserved but also recently built ones as non-destructive techniques reduce the volume of intervention to a minimum, thus lowering the overall economic and environmental cost (Morales Conde, et al., 2014).

According to Riggio (2013) the following circumstances can cause an assessment:

- The results of a periodical check
- Expiration of lifetime
- Errors in planning or construction become known
- Change of use of the building, codes or load-carrying
- Visible damages
- Inadequate serviceability and usability
- Exceptional incidents/accidents that damaged the structure
- Suspicion about structural safety due to inherent impairment of construction or material
- New intervention on the structure (preliminary evaluation)

There are multiple reasons for enhancing the use of non-destructive techniques for building assessments and due to modern structural knowledge and technically possibilities the feasibility to do so is given. The available techniques are numerous and some chosen assessments methods are presented in the following chapter, along with semi-destructive and destructive techniques.

3. State of the Art of Assessment Techniques

The reasons for an assessment of timber structures are plentiful as stated above. However, when dealing with an historic building it is vital to perform the assessment with as little damage as possible and according to Hasenstab (2006) special regards need to be paid to detecting hidden cavities and inner rottenness/decay as they can lower the stability significantly. In the following, assessment techniques are described with a focus on non-destructive and semi-destructive techniques. Afterwards, the combination of several non- and semi-destructive techniques will be reviewed.

3.1 Non-Destructive Techniques

3.1.1 Visual Inspection

Method

The first step of an assessment should always consist of a site visit with a visual inspection of the structure to receive an impression of the building and its condition. In other words, "Visual inspection cannot be substituted by any other method of inspection. It must be the starting point of the surveying" (Palaia, et al., 2008, p. 9). Especially, if no plans of the building to be investigated exists, it is a vital method to get an overview of the structure and individual parts.

The main purpose of this method is to identify, locate and document vital parts of a structure and investigate the material quality. For example, cracks, surface deterioration, decay or general external damage can be detected and marked as shown in the figure below. Through the visual inspection, the further procedure can be planned in accordance to the accessibility of structural elements, material quality and general state/stability of the structure.

Figure 6 - Example of Crack Measuring; Example of Crack Mapping (Dietsch, Philipp, & Heinrich, 2011).

Limitations

The biggest limitation of this method is obviously that it is not able to detect interior decay and damage. Also, if elements are hidden behind cladding or if the inspector is lacking experience, the method reaches its limits (Bartůňková, 2012).

3.1.2 Moisture Content Estimation

Method

Estimating the moisture content is a vital procedure for every assessment as it allows further estimations on the state of the timber since high moisture content can be associated with bio-deterioration (Riggio, et al., 2013). The only method to exactly determine the moisture content is through the oven dry method, however, this method requires removal of wood and therefore might not be desirable. Yet, for the estimation, in general three methods can be applied: The resistance-, the capacitance- and the hygrometric method (Riggio, 2013). For this study, the resistance method will be used and therefore it will be the only one described.

The resistance method uses a moisture meter with two pin-type electrodes and the connection between moisture content and the timber's direct current conductance to estimate the moisture content (Riggio, et al., 2013). The two electrodes that are only non-conducting at the tips, are driven into the wood and the electrical resistance between the two tips is measured (Lehmann, et al., 2010). According to Riggio et al. (2013) the tips should be at least 50mm apart from each other and measurements shall be taken in different depths of the element. If the species is known the taken readings can be adjusted to it using calibration curves of the respective species (Lehmann, et al., 2010). If the species is unknown, the readings can only be taken as approximate since a species correction is not possible (Riggio, et al., 2013).

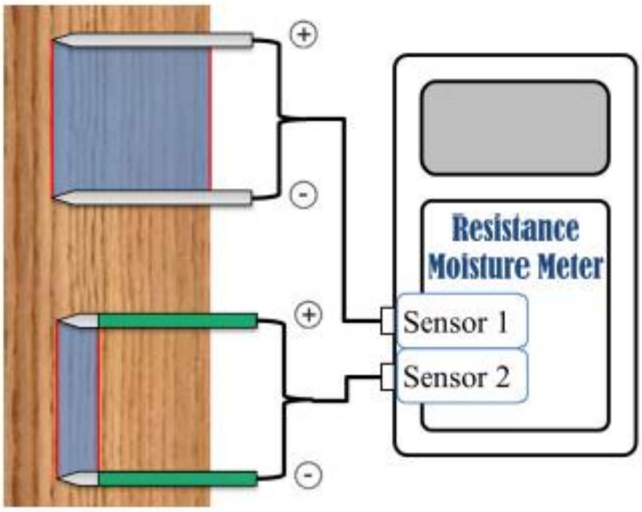


Figure 7 - Schematic of Resistance Method with Insulated and Non-Insulated Electrodes (Dietsch, Franke, Gamper, Franke, & Winter, 2015).

Limitations

The resistance method can only be applied for elements with a moisture content of about 7-30 % and requires temperatures between 5 and 60 °C (Riggio, 2013). Additionally, "the presence of some preservatives, flame retardant treatments, or other chemical or surface treatments may affect the accuracy of the measurement and require special calibration of the instrument." (Riggio, et al., 2013, p. 7).

3.1.3 Ultrasonic Method

Method

For decades, ultrasonic methods have been used to analyze the inner structure of construction material such as concrete, steel, stone or wood (Krause, et al., High-precision structure recognition of wooden construction elements with 3D ultrasonic (Hochgenaue Strukturerkennung von Holzbauteilen mit 3D-Ultraschall), 2013). It allows detection of interior defects or deterioration in wood and can also be used to estimate mechanical properties (Kasal, 2010). In general, two methods are used for the assessment of wooden elements, the pulse-echo and through-transmission.

The through-transmission method sends an ultrasonic impulse through an element and records the time the sound wave needs to pass the element (Hasenstab, 2006). As it is shown in the figure below, the waves will have to encircle any obstacles such as cracks, resulting in higher transmission times (Morales Conde, et al., 2014). However, the wave velocity is also influenced by properties of the tested element like moisture, density or porosity (Hasenstab, 2006). For accurate results, it is of great importance that transmitter and receiver of the impulse are on the same location on opposing sides of the element as the shortest distance between transmitter and receiver is used for the calculation of wave velocity (Hasenstab, 2006). By stepwise relocating the testing probes alongside an element the whole inner structure of it can be scanned for irregularities (BAM, 2004).

Figure 8 - Schematic of the Through-transmission Method (Baron, 2009).

The other ultrasonic based method is the Pulse-echo method. As the name indicates, it operates by sending an impulse and recording the echo of the transmitted sound waves (Hasenstab, 2006). Thereby, transmitter and receiver are located on the same side of an element and once the waves reach the end of an element, they are reflected back and recorded by the receiver. However, if a defect lies within the path, the waves are reflected earlier, indicating a crack or cavity for example. According to Tannert, Kasal & Anthony (2010) a clear back wall echo can therefore be seen as an element without defects. This is also very helpful as "using calibrated values, it is possible to determine the thickness of beams where the back wall is not accessible and to get an insight on the inner structure of elements." (Tannert , et al., 2010, p. 2).

Figure 9 - Schematic of the Pulse-echo Method (Baron, 2009).

Both methods operate in a grid that is drawn on the investigated element and waves are sent back longitudinal (in grain direction) and transversal (perpendicular to grain direction) (Krause , et al., 2013). Usually, the used frequencies are ranging from 20kHz to 200kHz since wood as a porous material has a high attenuation and high frequencies would decrease the depth of penetration (Hasenstab, 2006).

The results of ultrasonic tests are visualized in A-, B- and C- scans, where A- scans represent the transmission time and pulse intensities from several scans along one side of an element (Tannert, et al., 2010). From several A- images, a B-image can be composed that shows a 2D cross section of the investigated element (Hasenstab, 2006). Lastly, the C-scan represents an interpolated, horizontal layer that results from combining several B-scans with the same offset and produces 3D information about the element (Tannert, et al., 2010).

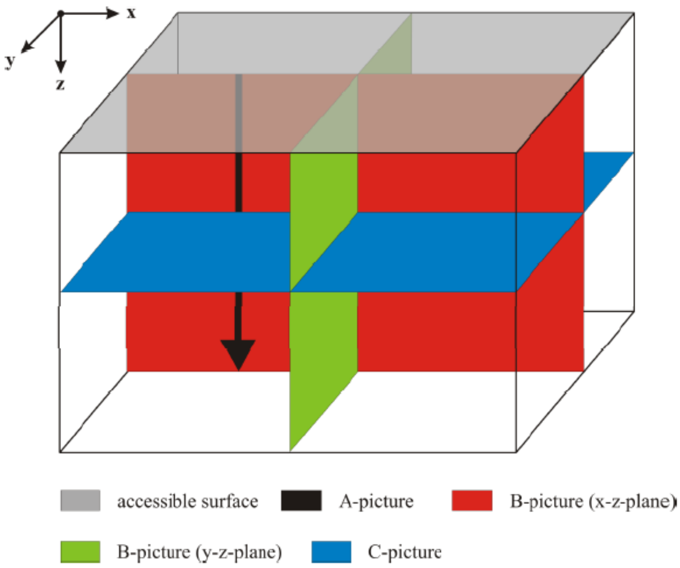


Figure 10 - Projection Planes for Ultrasonic Scans (Riggio, 2013).

Limitations
The ultrasonic technique is influenced by several aspects that have to be taken into account when using this method. According to Lechner (2013, p. 30) the "wood species, moisture content, temperature, biological and chemical degradation, decay, insect attacks, grain angle and measurement direction" must be known for the evaluation and interpretation of results.

As stated above, the technique is very useful for finding hidden defects, yet when encountering those, it is hard to distinguish between a large one and several small ones as well as classifying what kind of damage is present (Tannert, et al., 2010).

Additionally, one major limitation, when using the through-transmission method is that access to two opposing sides is necessary. However, accessibility in general plays a vital role since cased or covered elements are not assessable, even with the echo method. Furthermore, if the surface is rotten, cracked paralleled or the back wall is shaded both techniques are not usable (Hasenstab, 2006). Also, ultrasonic scans require a smooth surface with a roughness of 3 to 5mm at most as it is then easier for the waves to penetrate the object (BAM, 2004).

3.1.4 Radar Scanning

Method
Radar scanning is often referred to as GPR (Ground Penetrating Radar) when used for assessments and is composed out of an electromagnetic wave pulse generator, power supply, transmitting and receiving antennas and a computer for signal processing (Tannert, et al., 2010). Ground penetrating radar operates by sending short-duration electromagnetic impulses into an object and detecting/examining their reflections (BAM, 2004). With the GPR it is possible to fast scan whole structural objects as the equipment can be moved alongside an element while scanning.

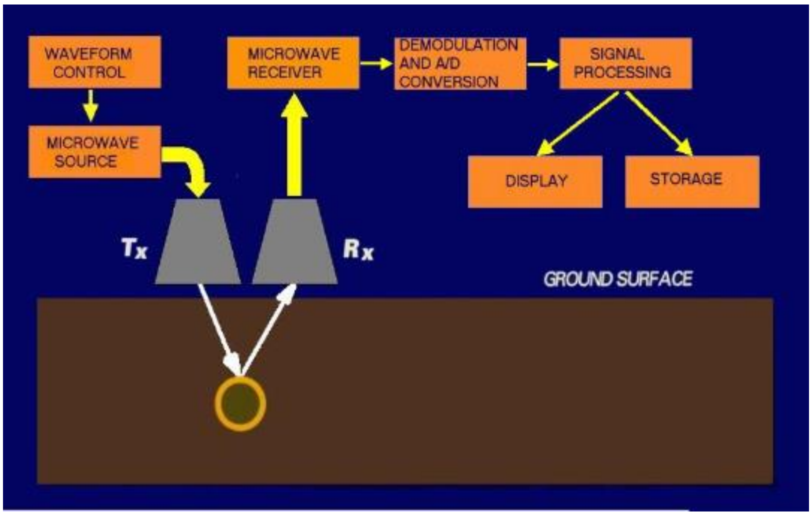


Figure 11 - Operational Principal of Ground Penetrating Surface (De Fino & Fatiguso, 2016).

Reflections are caused when the waves encounter material interfaces of different dielectric constants (Riggio, et al., 2013). According to Riggio et al. (2013) these can be a contrasting interface between sound wood and an air-or water-filled void, rotten timber, hidden elements such as steel bolts or the backside of the object investigated. The ground penetrating radar produces 2D radar images that are developed from a series of measurements where the system "records the two-way travel time and amplitudes of signal reflections as a function of travel time." (Ullberg, 2011, pp. 7-8).

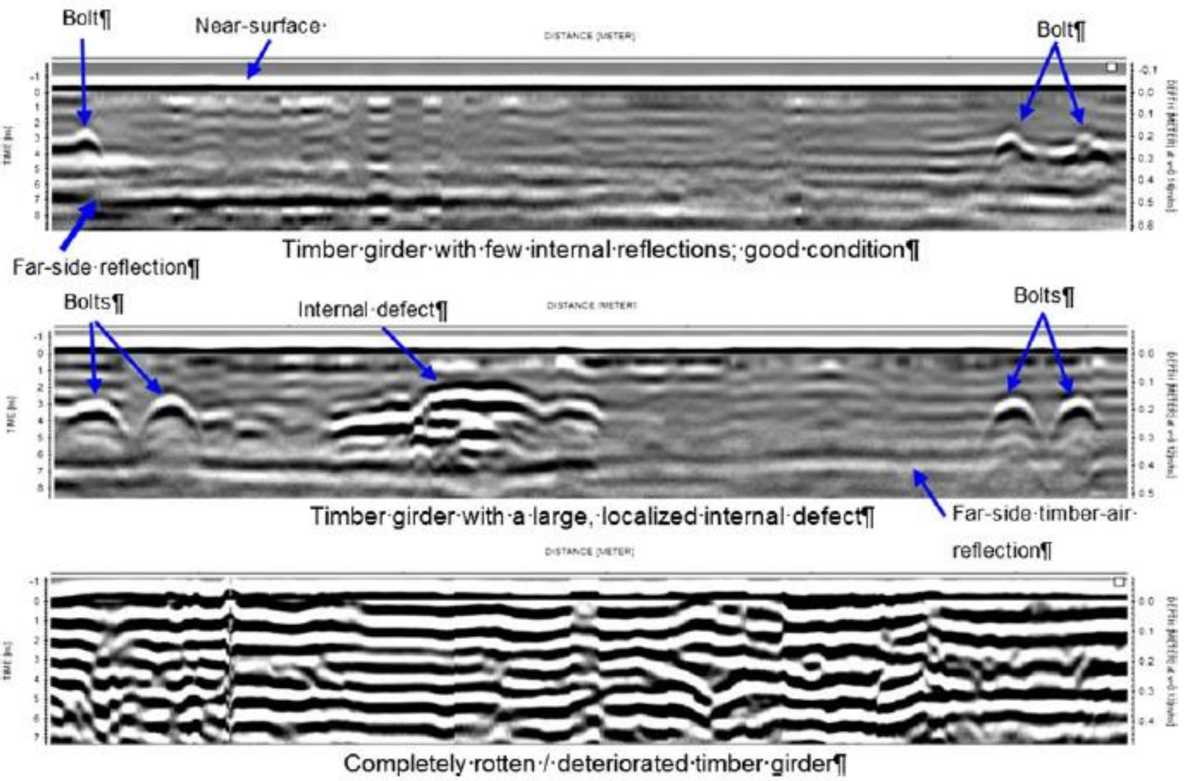


Figure 12 – Radar Image Showing Several Damage Patterns (Riggio, et al., 2013).

Highly influencing to radar scans is the moisture content of wood as water affects electric and dielectric properties (BAM, 2004). As a result, radar signals are slowed, mitigated and spread, yet, it is therefore also possible to use radar scanning for moisture detection (Riggio, et al., 2013). The depth of penetration is additionally influenced by the frequency, where high frequencies result in higher resolution but lower penetration depth compared to low frequencies (Riggio, et al., 2013). Therefore, high frequency antennas are more suitable for thin objects while thicker elements require low frequency ones. The GPR also has high tolerance towards rough surfaces and can also be used with only one accessible side, however, if two opposing sides are available, a metal plate can be placed on the back side of the element to receive a clear reflection that clearly indicates the back wall and proves the penetration of the whole element (Tannert, et al., 2010).

Limitation

The ground penetrating radar has several beneficial characteristics for in-situ use as is it applicable with one-sided access and to rough surfaces. On the other hand, it is highly influenceable by moisture and density variations which can disturb the depth information (Tannert, et al., 2010). Furthermore, if the thickness of an element is unknown, the frequency has to be adapted as resoultion or penetration depth might be too low. Additionally, the technique is limited in detecting thin defects and the interpretation of gained data as well as post-processing of that requires a high level of expertise (Riggio, et al., 2013).

3.1.5 Thermography

Method

Thermography is used as an assessment tool for several construction materials and can be used to measure heat losses in buildings or the surface temperature distribution and heat radiation of an object (Hasenstab, 2006). There are two approaches for thermography, the passive one where the individual elements are naturally warmer or colder than the background and the active one where the investigated elements are heated with an energy source and then observed in their thermal behavior with an infrared camera (Riggio, 2013). Thereby, active thermography is used more often in assessments as it also records the cooling behavior of an object. This reveals areas of different thermal conductivity, heat capacity and density as these differences appear in inhomogenities and show a faster or slower cooling behavior (BAM, 2004). Furthermore, active thermography is able to detect plastered or hidden elements, decay and enhanced mositure as their presence also results in different thermal properties and cooling behavior (Riggio, 2013). However, the method is only able to visualize information on or close to the surface and therefore only able to detect inhomogenities or defects up to a depth of approximately 10cm (Hasenstab, 2006; BAM, 2004).

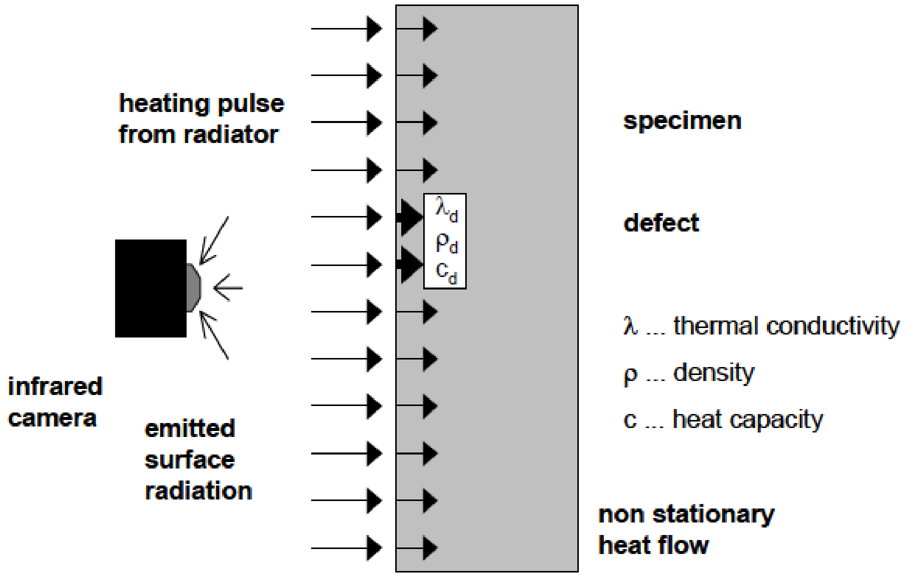


Figure 12 – Principle of Active Thermography (BAM, 2004).

Active thermography has been used in civil engineering mainly in two styles: the impulse thermography and the pulse-phase thermography *(Milovanovic & Pecur, 2016)*. Both styles use the same experimental setup and data acquisition that has been described and can be seen in the figure above *(BAM, 2004)*. However, the impulse-thermography method analyzes the data as a function of surface temperature versus cooling time and produces different curves by comparing the data of sound areas to those with irrgeularities *(Maierhofer & Röllig, 2009)*. The pulse-phase thermography on the other hand goes further and also analyzes the frequency of transient, thermal waves resulting from the heating *(Maldague, Galmiche, & Ziadi, 2002)*. Data gained from the impulse thermography is thereby "analyzed in the frequency domain via Fast Fourier Transformation of the transient curve of each pixel in a series of thermal contrast images. Defects lead to changes in amplitude or phase of the corresponding images." *(Maierhofer & Röllig, 2009, p. 2)*. Some authors *(BAM, 2004; Maierhofer & Röllig, 2009)* see the pulse-phase method as superior because it delivers more information from greater depths and produces phase images with higher resolution and less sensitivity towards optical characteristics.

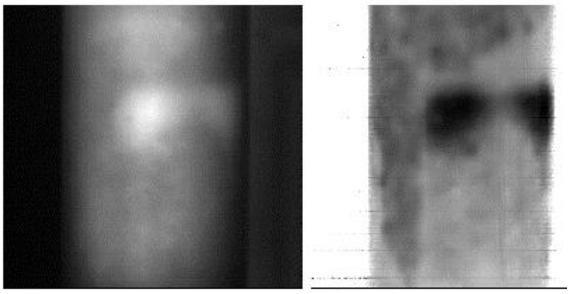


Figure 13 – Thermal Contrast Image (left) from Impulse Thermography and Phase Image (right) from Pulse-phase Thermography (BAM, 2004).

Limitation

As stated above, an assessment using thermography is limited to the surface and surface-near area (up to 10cm) of an object. Therefore, the decay and moisture detection/mapping and the detection of inhomogeneities or defects are solely representative for the outer part of an element and do not give confidence about the inner state of the element (BAM, 2004; Riggio, 2013). Additionally, radiation energy from the sun for instance should be avoided as well as wind and dust as they affect the gained data (BAM, 2004). Lastly, the active approach is limited to the accessibility of an object as it needs to be closely heated when this method is used (Riggio, 2013).

3.1.6 Radiography

Method

Different from concrete or stone where radiography cannot be applied due to their high density and absorption of radiation, timber as a porous material is very suitable (Tannert, et al., 2010). The method penetrates an element with energy from radiation beams and through the remaining energy that passed through the object, the internal structure is captured on an image (Nowak, 2013). Other sources of radiation such as electrons, neutrons or gamma rays can also be used for assessments. However, especially in-situ, X-rays have been found superior as they are not affected by electric or magnetic fields and do not require a permanent power source as gamma rays (Kasal, 2010; Nowak, 2013). Modern X-ray systems with sensitive plates and scanners are often used for in-situ work as they offer immediate display of images and can be applied in areas with limited access, yet, access needs to be given to opposing sides (Kasal, 2010).

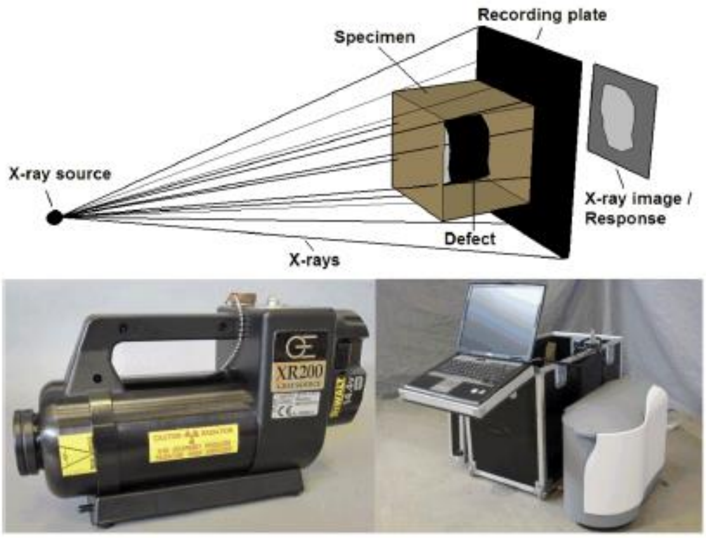


Figure 14 – Schematic of an X-ray Scan Setup (top) and X-ray Equipment (bottom) (Lechner, 2013).

Similar to X-ray scans that are used in medicine to detect injuries such as fractures, when used to assess a building this technique can detect inner damages or irregularities such as deterioration, metal objects, decay and disruptions of the grain structure caused by insects, drill holes or voids (Löwenmark, 2009). Even growth rings can be visualized with X-rays as the low mass attenuation of wood allows the use of low energy levels that produce high resolution images and thanks to modern computer programs, images can be further enhanced to even distinguish between subtleties that are otherwise only detectable through destructive testing (Kasal, 2010). Through an analysis of the results, the material's density as well as the overall structural quality can be estimated and the method can easily be used in-situ due to modern, small and handy X-ray devices as shown in the figure below (Nowak, 2013).

Figure 15 – Experimental Setup of X-ray Scanning (left) and Captured Image of a Wooden Beam with Metallic Elements Inside (right) (Riggio, et al., 2013).

Limitation

The main limitation of the X-ray scanning is that the produced images are two dimensional as the object is penetrated by radiation beams only in one direction (Tannert, et al., 2010). Therefore, estimations on deterioration, decay and the detection of internal flaws can be difficult as orientation and size must be parallel to the radiation and of adequate size (≥ 2% of member thickness) (Riggio, 2013). Furthermore, the density estimations only represent the average density over the depth in one direction of the element and can be influenced by decay (Löwenmark, 2009). To avoid this limitation, images from aside and above are required which of course can be difficult or impossible in-situ as both or even opposing sides might not be accessible (Löwenmark, 2009). Although, with evolving technology, modern radiography equipment has become much safer and requires less energy, considerations when working with radiation must always be taken, especially when investigating thicker objects that require high energy to be penetrated (Tannert, et al., 2010). Therefore, portable equipment often comes with a maximum energy level for saftey reasons, however, this can be limiting as thick objects might not be penetratable or produce blurry images (Löwenmark, 2009).

3.2 Semi-Destructive Techniques

3.2.1 Resistance Drilling (Resistograph)

Method

One of the most used semi-destructive assessment method is the resistance drilling (Resistograph) that penetrates the wood with a micro drill of 1.5 to 3.0mm (Nowak, 2013). The method is used with special equipment (Figure 13) that drills the needle-like drill head with a high, yet, constant number of rounds and constant advance into the wood while recording the energy required by the engine to perform the advance steadily (Hasenstab, 2006). Thereby, it is vital that the drilling is done prependicular to the surface in order to assure the accuracy of the penetration depth. From the required energy, estimations can be made on the hardness of the timber and eventually the density (Nowak, 2013).

The results of the resistograph are shown as a graph (Figure 14) with the penetration depth on the x-axis and the correlated amplitude on the y-axis (Nowak, 2013). As the drill advances, it encounters interfaces of different densities which results in an in- or decreasing amplitude as the encountered resistance changes (Riggio, 2013). The amplitude is thereby pretty sensitive and allows to see not only irregularities like knots or cracks but also growth rings (Löwenmark, 2009). Depending on the level of the amplitude, it is even possible to distinguish between early- and late-wood due to their different densities (Hasenstab, 2006). Additionally, it is possible to change the amplitude's scale if an object with several highly different densities is investigated.

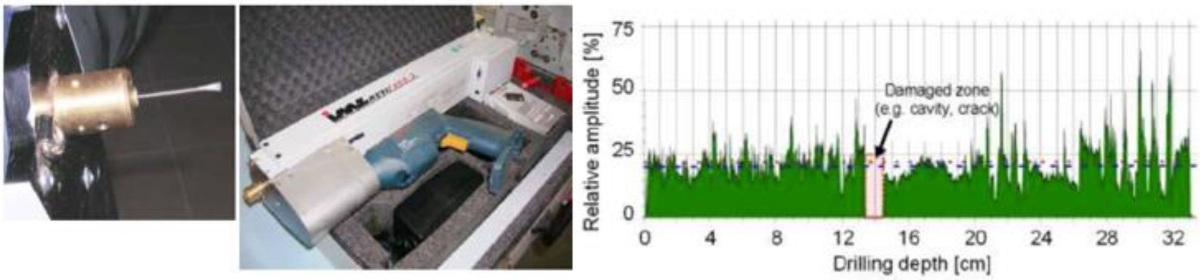


Figure 16 - Resistance Drilling Equipment; Result of a Resistance Drill Visualized as a Graph with Penetration Depth and Encountered Resistance (Riggio, 2013).

Limitation

The main issue with this technique is that it is unfit to scan whole elements but only represents point measurement information that lies within the drilling path. Therefore, its use is highly related to other assessment methods as when used solely, one has to be lucky to detect inner defects (Nowak, 2013). However, it is a very precise technique to identify and more accurately locate hidden flaws that were indicated by ultrasonic or X-ray images (Baron, 2009). Another limitation, especially when used in-situ on historic structures, is that the method is semi-destructive which leaves boreholes that could be undesirable.

3.3 Case Studies and Combination of Methods

Many studies have been done on historic buildings, using a combination of several NDT's and sometimes SDT's with the aim of reliable assessments of the material quality and overall stability of the structure while preventing interventions or replacements as much as possible (Nowak, 2013; Lechner, 2013; Hasnikova & Kuklik, 2014; Palai et al., 2008; Bartůňková, 2012). The assessment methods reviewed in this study can be used for estimations of some timber properties, yet, an assessment based on a single method is considered insufficient by several studies (Tannert et al., 2010; Bartůňková, 2012; Baron, 2009; Lehmann, et al., 2010; Kasal, 2010; Hasenstab, 2006; Henriques, Nunes, Machado, & de Brito, 2011). Combining several methods in an assessment can not only result in more information on different properties but also demonstrates correlation between results (Baron, 2009).

Independent of the individual study's aim and objectives, many researchers agree that even though modern testing equipment is indispensable, one of the most vital methods and the one every investigation should begin with, is the visual inspection (Palaia, et al., 2008; Lehmann, et al., 2010; Kasal, 2010; Riggio, et al., 2013). Palaia et al. (2008) also suggests, if available, to study and analyze documental and graphical information in order to establish a structural design before visiting the site. However, visual inspections are always bound to the knowledge/expertise of the inspector towards the material as well as its signs of deterioration and can solely detect surface damages (Lehmann, et al., 2010). Yet, visual inspection can be seen as the first scan of a structure and irrgeulatities or areas of interest/concern should be marked for following assessment mehtods (Riggio, et al., 2013).

Most studies recommend, to identify the species and to estimate the moisture content of timber elements as a next step. Knowing the species allows estimations on the density and the moisture content on the presence of fungi or decay and is also substantial information for other methods that are influenced by moisture such as ultrasonic or radar tests (Lehmann, et al., 2010; Baron, 2009; Hasenstab, 2006; Lechner, 2013). Especially, the velocity of ultrasonic waves was found to be influenced by moisture, as, below the point of fibre saturation, their speed decreased with increasing mositure (Baron, 2009).

In order to make estimimations on the internal state of an element, modern equipment is needed as it is able to assess without harming the material. Knowing the inside condition of a member can provide information on deterioration, decay, hidden elements, voids and other flaws, damages or irregularities that need to be considered for a dependable assessment of individual members and the overall structure (Riggio, 2013). Methods that proofed to deliver this information are radar scanning, ultrasonic- and X-ray testing according to Riggio et al. (2013), Baron (2009) and Hasenstab (2006) to name a few. All techniques were found suitable to fast scan structures, yet, several authors agreed that ultrasonic testing is inferior when it comes to scanning large structures/areas in short time as it visualizes moisture in higher quality, is usable for hard-to-access elements and those behind metal shields (Tannert, et al., 2010; Palai, et al., 2008). In general it can be used to distinguish between damaged and undamaged elements and can be relied upon for strength and stiffness estimations (Lehmann, et al., 2010; Bartůňková, 2012). However, when the through-transmission method is applied, opposing sides of a member are needed, limiting the use of this technique. Also, the impulse-echo mehtod, that only requires one-sided access, is limited to the element's thickness, which cannot be greater than 25cm and is unusable when metallic elements are present (Lehmann, et al., 2010). According to Hasenstab (2006) transversal waves (50kHz) also proofed to be superior for thick elements (≥10cm) while longitudinal waves (100kHz) were found to be better for thin elements (≤10cm) yet were in need of ultrasonic gel for smooth and vaseline for rough surfaces. A higher tolerance towards imperfect surfaces showed the ground penetrating radar that is also applicable from only one side (Riggio, et al., 2013). While radar scanning, ultrasonic- and X-ray scanning are commonly used to estimate strength and stiffness parameters as well as detecting inner irrgeularities, thermography is however rarely applied as it only investigates the near surface area for moisture or decay and sometimes is more work/energy-costly (Riggio, 2013; Hasenstab, 2006; Walther, 2012).

Several studies, being aware of the individual limitations of the used methods, applied a combination of assessment tools, especially to confirm the findings from scanning techniques. Many preferred to apply resistance drilling to verify density estimations or internal defects, which were also successfully located with the Resistograph (Tannert, et al., 2010; Palai, et al., 2008; Hasenstab, 2006). Hastenstab (2006) additionally combined ultrasonic and X-ray images to reduce misinterpretations and early detection of flaws. However, resistance drilling is a semi-destructive technique and when a historic structure is investigated it sometimes is not considered in order to not harm the structure further (Hasnikova & Kuklik, 2014; Lechner, 2013; Morales Conde, et al., 2014).

With a combination of non-destructive techniques, the conservation of historic structures is possible as seen in the study of Morales Conde et al (2014) where a residential building of substantial heritage value was assessed using visual inpsection, ultrasonic velocity transmissions and moisture measuring. The study found deterioration and decay in several pillars that lead to a sustainable intervention conserving most of them. Additionally, financial costs as well as environmental costs, in terms of energy consumption and CO_2 emissions were lowered by almost 75%, compared to a total replacement job. On the contrary, Hasnikova & Kuklik (2014) investigated an old railway station by using ultrasonic testing, Pilodyn as well as crack depth measuring and concluded that many members of the structure had to be replaced and only some could be reused. Another study (Lechner, 2013) investigated among others structures, the Vasa warship that sunk due to constructional errors shortly after completion and is now exhibited in Stockholm. X-ray measurements were used as a NDT and information on the density of the ship was produced that "would be of great help when it comes to creating a new support system using advanced technology in order to protect the Vasa warship in the future and prevent further deformation in the ship structure." (Lechner, 2013, p. 56).

Examples of studies using or investigating non- and semi-destructive techniques are plentiful and show the benefits these techniques have, especially when dealing with historic structures (Morales Conde, et al., 2014; Palai, et al., 2008; Lechner, 2013). However, many authors suggest further research as some techniques are not used to their full potential as they are used in timber structure assessments for a relatively short time (Tannert, et al., 2010; Lechner, 2013; Kasal, 2010). Lechner (2013) also suggests an assessment strategy or guideline for the use of the different techniques that need to be easily adaptable as every structure is unique in a way, especially histotical ones.

4. Available Standards and Guidelines

Although numerous studies, focused on non-destructive assessments of wooden structures, exist, only a few standards, codes and norms can be found on this subject which has been criticized by several authors (Tannert et al., 2010; Löwenmark, 2009; Rug, 2014).

4.1 International standards

4.1.1 ISO 13822 (2012)

On international level one of the few standards that is currently available is the ISO 13822 (2010) "Bases for design of structures – Assessment of existing structures" that focuses on the assessment of existing structures. The standard's procedure for a general assessment is divided into the following two parts:

- Preliminary assessment: A first study of available documents and other information related to the structure, followed by a visual inspection where the structural system is identified, defects visible to the bare eye are documented and graded qualitatively in terms of structural conditions. Next, preliminary checks that are not further specified by the standard, should identify critical deficiencies and judge if immediate actions are required due to potentially dangerous conditions and if further, detailed investigations are necessary or recommendable.

- Detailed assessment: If the preliminary assessment recommends further investigation, a more detailed study of documents, regulations and topography at site is required. The following detailed inspection then includes a geometrical survey of the structure and its members as well as material testing. Based on the analysis of results of the investigation, the necessity for actions and the properties of the structure are determined. Lastly, a structural analysis should be done to verify the reliability of the structure. However, if the results of the detailed assessment are incomplete or further inspections are required, the procedure is to be repeated until the results are satisfactory.

The assessment is completed with a report where the structural safety and serviceability is evaluated and whether the structure is sufficiently reliable in which case no interventions are needed or if not and repairs or even demolition is required. However, since this study is focused on the assessment, these parts of the standard are not discussed further. The overall procedure according to the ISO 13822 (2010) can also be seen in the flowchart below.

More important to this study is the annex "I – Heritage structures" where an altered procedure concerning structures of cultural heritage can be found. It is recommended that the assessment should be carried out by a multidisciplinary team including not only architects or engineers but, among others, also historians or cultural heritage managers. The assessment procedure is again divided into a preliminary and a detailed one, however, it is recommended to solely use non-destructive or semi-destructive techniques. Destructive testing should only be considered or used if "the potential gain in information obtained shall outweigh the loss of heritage value, i.e. the losses resulting from the tests should be less than those that would be caused by the more severe interventions necessitated by poorer understanding of the structure." (ISO 13822, 2010, p. 39). In general, it is empathized to avoid interventions and sample taking as much as possible and only as a last resort.

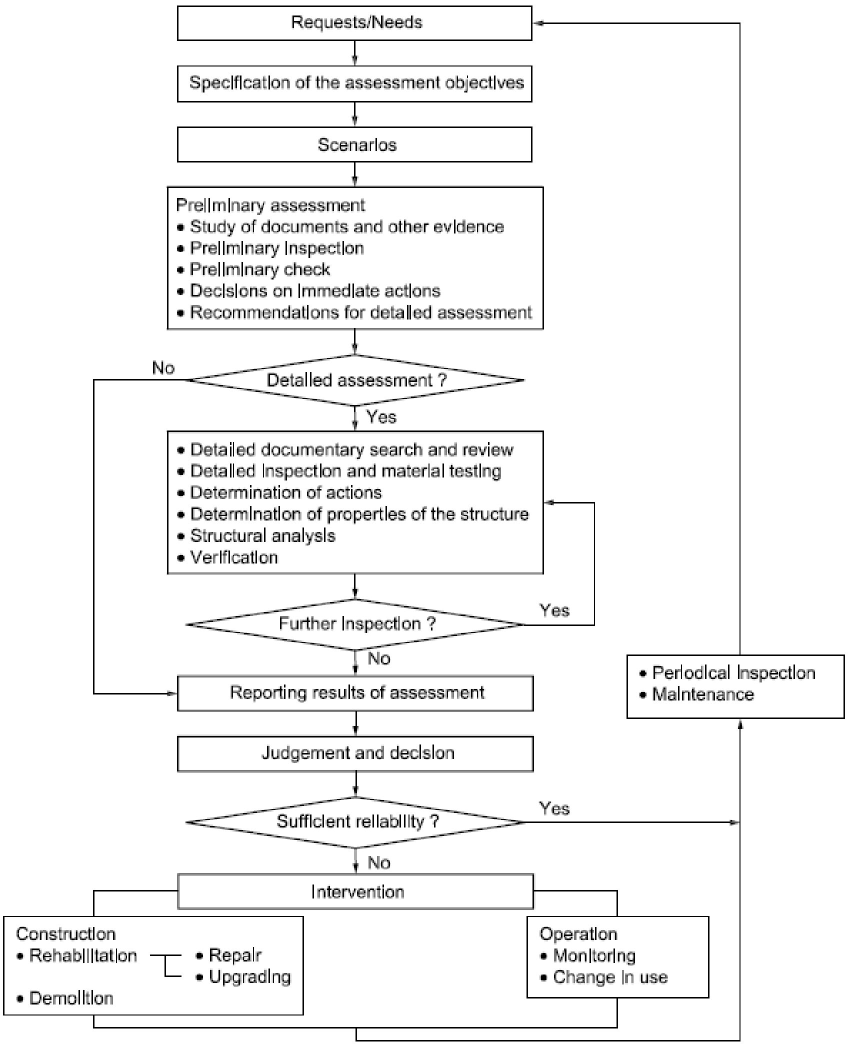


Figure 17 - Flowchart for the General Assessment of Existing Structures (ISO, 2010).

Problematic with the ISO 13822 (2010) is that it is not focused on one specific material. This has also been criticized by some authors (Macchioni & Bertolini, 2011) who lamert that although the standard concerns on-site assessments, it is based on several constrcution materials and therefore too general for practical use for wooden structures. Additionally, the standard does not refer to specific assessment techniques that could be used but only suggests, in the annex "I - Heritage structures", the use of non-destructive techniques to protect cultural heritage.

4.1.2 Eurocode 5 (EC 5/ EN 1995)

Another international standard on the subject of assessing existing structures is the "Eurocode 5 – Design of timber structures". However, the standard and its national annexes are based majorly on the design of new structures and the structural calculations for its elements and less applicable for existing standards, especially when they should be assessed in a non-destructive way (Rug, 2014). In case of the German annex Rug (2014) complaints that it principally just contains regulations made for newly cosntructed buildings although, in Germany, the construction volume in the field of preservation, overhaul and rennovation or modernization makes up 70% to 80% of the total construction volume (Rug, 2014). Rug additionally criticizes that ultrasonic procedures for older buildings to nondestructively estimate the modulous of elasticity for instance, are not yet permitted in Germany and no standrads or annexes to the EC 5 exist, even though the procedure has proven beneficial. In general, the german standards or annexes of the EC 5 that concern timber structures are either, as mentioned, for new timber buildings, concerning the protection of wood from decay or fire, or focus on mechanical roperties that are mainly determined through destructive methods (Rug, 2014).

4.2 National Standards

4.2.1 UNI 11119: 2004

The italian standard UNI 11119: 2004 "Goods Cultural Heritage – Wooden Artefacts - Building structures – in-situ inspection for the diagnosis of the elements in operation" is one of the few standards that focus solely on assessments for historic timber structures. The standard aims to estimate mechanical performances and classifies wooden elements by using a diagnostic path. The diagnosis is mainly done through a visual inspection where the structure is observed as a whole and other information on wood properties are documented (Lenzi, 2008).

The diagnostic path starts with the identificatio nof the wood species where a reference is made to the standard UNI 11118 that suggests taking small samples for microscopic examination if the macroscopic examination is not sufficient (Lenzi, 2008; Fatiguso, De Fino, Scioti, & Rubino, 2016). Next, the moisture content should be measured in-situ, using an electric hygrometer with reference to the standard UNI 11204 (Lenzi, 2008; Fatiguso, et al., 2016). From the moisture content, the class of biological risk can be determined with reference to the standards EN 355-1 and EN 355-2. Afterwards, a geometric survey is to be performed that includes the dimensioning of structural elements and the measurement as well as documentation of deformations, growth characteristics, defects, degradation and other damages (UNI, 2004). Through the geometrical survey, critical areas and members can be identified and classified according to their resistance, using tables provided by the standard (UNI, 2004). For interior defects or irregularities, necessary for the classification, the standard suggests to use non-destrcutive tests, such as the ultrasonic technique, yet, it does not specify when and how to use which technique (UNI, 2004). Other studies have recoursed to other additional techniques such as radar- and thermographic scans or resistance drillings (Fatiguso, et al., 2016; Lenzi, 2008). Once the structural elements are classified according to their resistance and species, estimations on the element's strength can be taken from the table (see figure below), provided by the standard. From this evaluation on the material qualtity and overall stability can be made.

Feature		Category in operation		
		I	II	III
Chamfer		$\leq$ 1/8	$\leq$ 1/5	$\leq$ 1/3
Various injuries Cracks from frost Nested pores		Absent	Absent	Eligible, but only to a limit
Single knots		$\leq$ 1/5 $\leq$ 50 mm	$\leq$ 1/3 $\leq$ 70 mm	$\leq$ 1/2
Knot group		$\leq$ 2/5	$\leq$ 2/3	$\leq$ 3/4
Inclination of the fiber (slope %)	In radial section	$\leq$ 1/14 (-7%)	$\leq$ 1/8 (-12%)	$\leq$ 1/5 (-20%)
	In tangential section	$\leq$ 1/10ß (-10%)	$\leq$ 1/5 (-20%)	$\leq$ 1/3 (-33%)
Radial cracking retraction		Eligible, as long as it does not pass		

Table 2 - Classification Rules for Wooden Structural Elements in Operation (UNI, 2004).

		Maximum Tension (N/mm²)					
Species	Category in Operation	Compression		Static Bending	Traction parallel to fiber	Cut (Parallel to fiber)	Flex elastic module
		Parallel to fiber	Perpendicular to fiber				
White spruce	I	11	2,0	11,5	11	0,9	13.000
	II	9	2,0	10	9	0,8	12.000
	III	7	2,0	7,5	6	0,7	11.000
Spruce	I	10	2,0	11	11	1,0	12.500
	II	8	2,0	9	9	0,9	11.500
	III	6	2,0	7	6	0,8	10.500
Larch	I	12	2,5	13	12	1,1	15.500
	II	10	2,2	11	9,5	1,0	14.500
	III	7,5	2,0	8,5	7	0,9	13.500
Pine	I	11	2,0	12	11	1,0	13.000
	II	9	2,0	10	9	0,9	12.000
	III	7	2,0	8	6	0,8	11.000
Chestnut	I	11	2,0	12	11	0,8	10.000
	II	9	2,0	10	9	0,7	9.000
	III	7	2,0	8	6	0,6	8.000
Poplar	I	10	1,5	10,5	9	0,6	9.000
	II	8	1,5	8,5	7	0,5	8.000
	III	6	1,5	6,5	4,5	0,4	7.000
Oak	I	12	3,0	13	12	1,2	13.500
	II	10	2,5	11	10	1,0	12.500
	III	7,5	2,2	8,5	7	0,9	11.500
1) The maximum tensile tension perpendicular to the fiber is assumed conventionally equal to zero							

Table 3 - Maximum Stresses According to Species and Category of Wooden Elements in Operation (UNI, 2004).

In general, the italian standard UNI 11119 is a very useful tool when investigating historic wooden structures as it sets a non-destructive diagnostic path for an assessment. Additionally, it indicates the use of specific technqiues for the determination of some wood properties, yet, it misses a more detailed suggestion on which technique is most fit to be used for the determination or estimation of required properties.

4.2.2 SIA 269

In recent years Switzerland has worked out a series of codes and guidelines for the maintenance and assessment of existing structures. The SIA 269 series "Existing structures" establishes rules for work on existing structures of several materials, including concrete, steel and timber (Steiger, 2010). Similarities in the assessment procedure towards the ISO 13822 can be seen as the standard was based on already existing swiss and international codes (Steiger, 2010). The SIA 269/5 " Existing structures – Timber strucutres" thereby regards timber structures and "contains detailed provisions regarding the condition survey in view of determining reliable updated characteristic values of resistance of timber material and connections as well as the corresponding updated resistance factors." (Brühwiler, Vogel, 2012 p. 280). According to Steiger (2010), the assessment is divided into three different phases, a preliminary-, general-, and detailed examination. As it can be seen in the figure below, the first phase, prelimnary examination, shows similarities to the ISO13822 as it includes only visual and simple checks. Depending on the level of satisfaction of the results a more detailed investigation is needed or not.

However, different than the ISO13822, the SIA 269 implements the study of documents related to the investigated structure firstly in the second assessment phase, general examination. Another difference occurs when dealing with cultural heritage as there is no annex to the SIA 269 for this case but a reference to the SIA 2017 that estimates the historic value of a structure (Steiger, 2010). Other than that the procedure is very similar and suggests the use of simple, mostly non-destrcutive tests for key areas and members of the structure (Steiger, 2010). However, if the general examination does not deliver sufficient results, the detailed examination forsees the use of destrcutive tests in laboratory and has to be repaeted several times if necessary (Steiger, 2010). Once the results of the detailed examination are satisfactory, a decision towards the safety and consequences for the structure can be made.

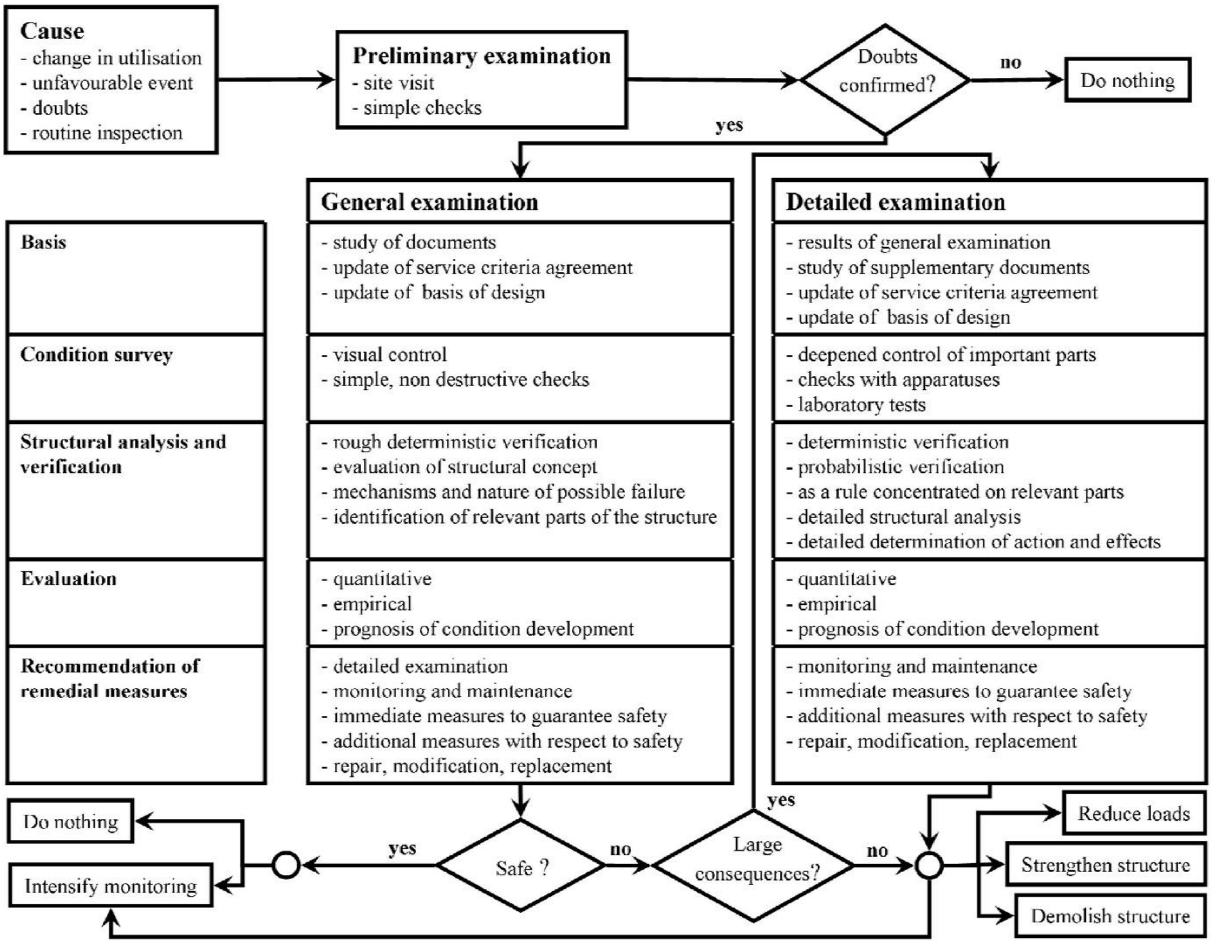


Figure 18 – Decision Path for Assessing Existing Structures (SIA 269, 2009.

The main and positively emphasized difference of the SIA 269 towards the above reviewed ISO 13822 is that the standard covers several construction materials seperately. However, as far as this study is aware, no regulations or suggestions are made on which techniques are in line for the non-destrcutive checks. Nonetheless, "series of SIA standards for existing structures is an original and pioneering initiative which may present a basis for similar initiatives in other countries" (Brühwiler, Vogel, 2012 p. 280).

4.3 Available Guidelines in Accordance with Standards

Besides existing standards like the ones reviewed above, guidelines, taking aspects from several standards into account, can be found. One such guideline was developed by Cruz, et al. (2015) helps with decision making and provides information on necessary criteria when assessing wooden structures in heritage buildings and "could be used as the basis for possible European Standards, as discussed with CEN/TC346 (Conservation of cultural heritage)" (Cruz, et al, 2015, p. 1). According to Cruz, et al. (2015) assessments needs to be distinguished between cultural heritage and common old wooden structures as structures of cultural heritage should experience repairs only as a last choice and justify greater expenses for the survey. The assessment procedure is split into three parts: A preliminary assessment, a detailed survey of timbers and a detailed survey of timber joints.

The preliminary assessment of a structure includes the following aspects according to Cruz, et al. (2015):

- The necessity for an assessment due to damage or change of use of the structure,
- The general principle that all inspections must be done in a non-destructive way,
- That interventions might be necessary immediately as of ongoing biological damage from insects or excessive moisture,
- And that the structure's condition is fit for an inspection in terms of safety, accessibility, lightning/visibility and clean surfaces.

The first step for the preliminary assessment is the desk survey where available documents, drawings, photos or other information regarding "the loading conditions during its lifetime, previous interventions or restorations" (Cruz, et al., 2015 p. 7) are studied. Following, is the preliminary visual survey where damages and other suspicious areas are identified and if necessary immediate safety/stability measures are done by specialists for timber structures (Cruz, et al., 2015).

The next step is the measured survey that is split into three parts:

- A geometrical survey including drawings of the overall structure, the dimensions and shapes of timber members, the different joint types and their material as well as the identification of historic significant elements,

- A technical survey where the species is identified, the moisture content is determined/evaluated, the environmental conditions are established and the date of the structure is determined through dendrochronology,

- And a defects and damage survey that identifies and locates biological-, fire- or mechanical damage, missing elements as well as hidden timbers.

Afterwards a structural analysis is carried out, based on the findings of the surveys. This should identify areas with high or critical stress that might require further inspections which is documented along with all other findings in a preliminary report.

If the preliminary report concludes further inspections (see figure below), a detailed survey of timbers is to be done. This closely follows the steps of the UNI 11119 standard and identifies the wood species, moisture content, characterization of biological risk and strength grading of the respective members (Cruz, et al., 2015). As in the standard, through visual inspection, the structural members are divided depending on the stresses they have to bear and when visual inspection reaches its limits, non-destructive techniques should be used, to complete the survey. However, Cruz, et al. (2015) does not specify on which techniques should or can be used. Yet, it is advised to check the gained results against those gained from other non-destructive methods to lower the uncertainty of the data (Cruz, et al., 2015).

Lastly, a detailed survey of timber joints is done, where the geometry of joints, the overall quality of workmanship, changes over time and the general timber quality is investigated. Thereby, the use of non-destructive techniques such as resistance drilling is suggested to obtain information on density and determine whether or not hidden objects or defects are present (Cruz, et al., 2015).

Although present in the decision path below, a diagnostic report and the correlated design of interventions is not covered by the guideline as it was outside the scope of the study (Cruz, et al., 2015). Nonetheless, the guideline developed by Cruz, et al. (2015) is one of a few in the field of in-situ assessments of historic timber structures even though it could be more precise on the non-destructive techniques that could be used for this kind of assessment.

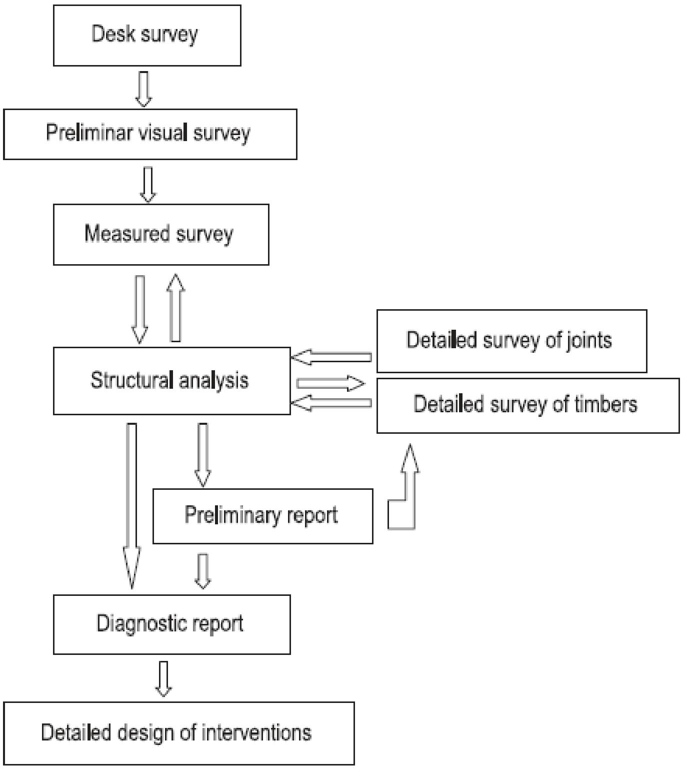


Figure 19 - Steps Required for the Assessment and Planning of Interventions in Historic Timber Structures (Cruz, et al., 2015).

5. Guideline for Assessment

The methodology of this study is to develop a guideline or best practice, evaluating which non-destructive technique can be applied to satisfy requirements set by available standards. The only standard available to this study that contained these requirements is the UNI 11119. Therefore, the following guideline/best practice will be based on this standard's requirements. In the following, individual steps of the standard are regarded in terms of their input, action and results. Additionally, decision paths were developed as a form of visual aid for the respective steps. Furthermore, additional useful information that can be determined/estimated through non-destructive techniques is described. Lastly, recommendations on the proper procedure of the individual techniques are presented.

5.1 Preliminary Assessment

5.1.1 Input

The first criterion is to gather all documents such as plans, photographs, load-bearing history, used materials and history of structural changes or recent interventions that are available. No equipment or NDT's are required for this criterion, however, it should be the first step of any assessment as long as sufficient documents are available and reliable.

5.1.2 Phase

The actual work of the preliminary assessment is to study all documents that were found and are related to the building and building-environment. Additionally, many authors and standards suggest a preliminary site visit as the next, or in case of a lack of documents, the first step.

5.1.3 Expected Results

The results expected from a preliminary assessment are to develop, if not already existing, a structural layout and in general to gain a first impression of the overall structure, its elements and their geometry as well as the quality of their material. The findings of this visit can later be visualized in a structural layout plan and individual schematics of the structural members of interest. Another important aspect of a preliminary assessment is to evaluate the stability of the structure and if immediate interventions are necessary to assure its safety during the following steps of the assessment.

5.2 Species Identification

5.2.1 Input

The species of a structure can be identified through reliable documents that clearly state the used type of wood. However, if these do not exist, macro- and/or microscopic inspection is required and if necessary, additional personnel with an expertise on wood species.

5.2.2 Phase

If documents on the used type of wood exist, these should be studied first, yet, if none are available or doubts still exist after their study, further steps need to be taken. Thereby, the manner of these steps depends on whether or not small damages to the structure, in form of sample taking, are tolerated. If allowed, the most reliable method to identify the species, is to take small samples and perform a microscopic inspection. In the case that sample taking is not allowed, a macroscopic investigation is needed that can be done during a site visit. For both inspections, external personnel with expertise on the subject might be needed as the identification of a wood type could be exceeding the knowledge of the inspector.

5.2.3 Expected Results

The expected result of this step is of course the clear identification of the species used. This is of great importance for the whole assessment as the species yields several information on mechanical properties of the type of wood which is vital for estimations on the structure's stability.

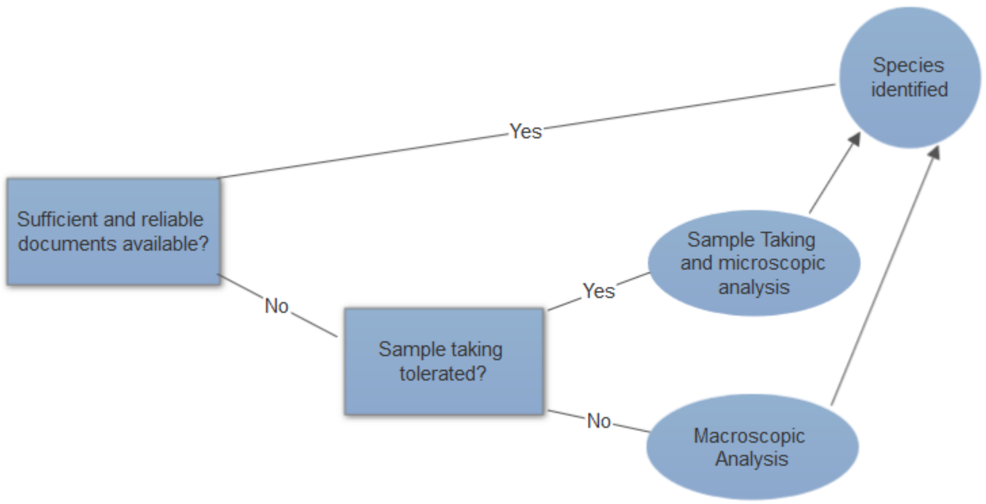


Figure 20 - Decision Path for the Identification of the Used Species.

5.3 Moisture Content

5.3.1 Input

For the determination of the moisture content, special equipment is needed. Again, depending if sample taking is tolerated, the actions to be taken differ. The most reliable and accurate method to determine the moisture content is the oven-dry method, however, it requires sampling. If that is not tolerated, other methods using a moisture meter, for instance the resistance method can be applied. In order to identify the cause for excessive moisture, visual inspection, a hygrometer for air humidity and enhanced visual inspection tools such as ground penetrating radar, radioscopy or thermography can be necessary.

5.3.2 Phase

As mentioned above, if tolerated, the moisture content can be determined through sampling and the oven dry method. However, if permitted, non-destructive methods, capable to be used in-situ are required. The resistance method is thereby a highly beneficial tool as it does not require a power source, is handy in its design as well as its use and comes with a set of different-lengthened electrodes. It uses an electrical hygrometer that measures the electrical resistance between two electrodes that are driven into the wood. The resistance method therefore allows quick and easy to repeat measurements in different depths and in a quasi-non-destructive style as the electrodes diameter is only of a few millimeters.

Measurements for moisture content should be done in every story of the investigated building and ideally for every individual structural member. When measuring the moisture content, it is important to penetrate the surface and below element in a perpendicular angle, in order to be able to accurately link the measured content to a certain depth. It is further important to choose an area for the measurement where no signs of excessive moisture are present to the surface so that the taken moisture content corresponds to the average one of the element. Also, the species must be known as the measured values need to be adjusted through calibration curves of the respective species. Most modern equipment is implemented with these calibration curves so that the moisture content is automatically adjusted. A good practice for the measurement is to turn off the equipment after every run as to avoid interference for the next measurement.

Other aspects when investigating the moisture content of wood, are to take the air humidity into account and raise suspicions when excessive moisture contents are found. The air humidity has a direct influence on the behavior of wooden elements as their moisture content is either a result of the air condition or from another source such as a leak where the wood is saturated locally. However, the air humidity is absorbed by a wooden element over its complete size and can result in cracks, when the air humidity is so low that the wood starts to tighten. On the other hand, when the air humidity is high, the wood will decrease in its mechanical behavior as it softens and furthermore, it becomes more vulnerable to biological decay from insects and fungi. Measurements of air humidity and temperature can be performed by implementing monitoring sensors.

5.3.3 Expected Results

First and foremost, the moisture content of the overall structure and individual elements will be determined. Thereby, one can identify critical areas and members that contain a high moisture content and thus could be targeted by decay from insect or fungi. However, through the analysis of the gained results and by measuring the air humidity within the building, the source of moisture, especially if excessive, can be detected as well. Therefore, vertical elements should be measured at different heights to detect rising dampness, condensation or infiltration. Possible sources of moisture can vary as the graph below shows exemplary.

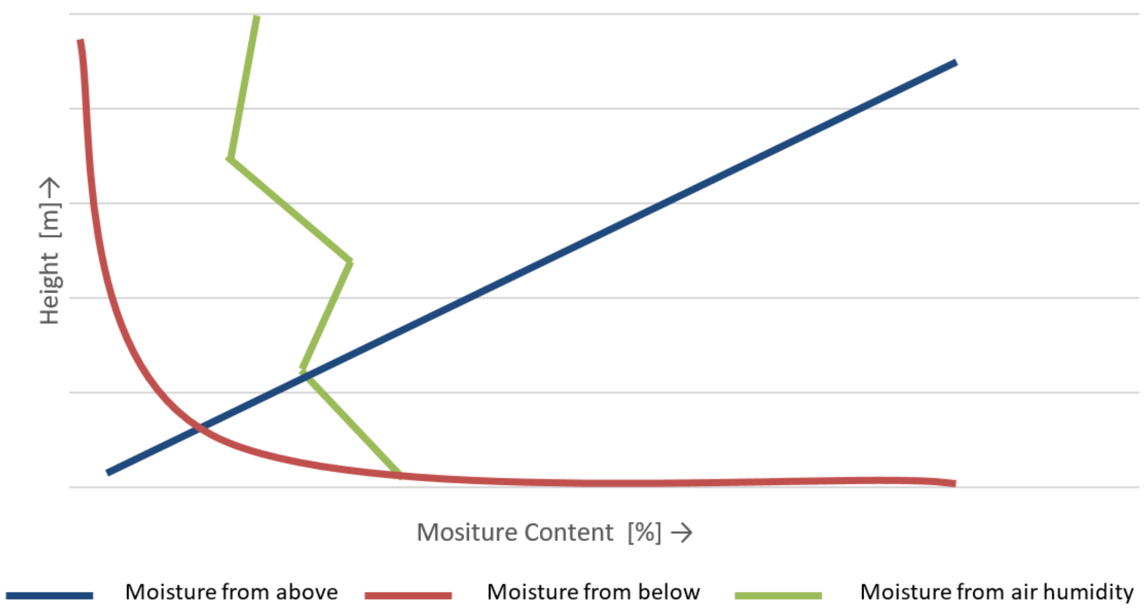


Figure 21 – Exemplary Depiction of Different Moisture Causes.

Additionally, when excessive moisture is present non-destructive techniques can be used to map the progression of moisture. Even visual inspection can be used for this, if extreme moisture is present on or close to the surface. However, for an accurate mapping of the moisture progression, the following enhanced visual inspection tools can be applied:

- Thermography: A highly beneficial tool as it only requires one-sided access and is able to clearly distinguish between moist and dry sections of structural elements by analyzing the surface temperature and cooling behavior of structural elements.

- Radioscopy: This enhanced visual tool is only applicable when opposing sides of the element are accessible as a recording plate needs to be applied at the back side to capture the X-rays. Excessive moisture can be detected through radioscopy as the density decreases when the wood is saturated (Naidoo, Zbonak, & Ahmed, 2006). Additionally, decay is often related to wooden elements with moisture contents exceeding 20% and can be detected by radioscopy.

- Radar: Another tool that only requires one-sided access is radar scanning. It can be used for the detection/mapping of moisture as it uses electromagnetic impulses to scan an object. These impulses are highly affected by moisture content as the dielectric constant is changed when an object is saturated, causing slower, mitigated or spread signals.

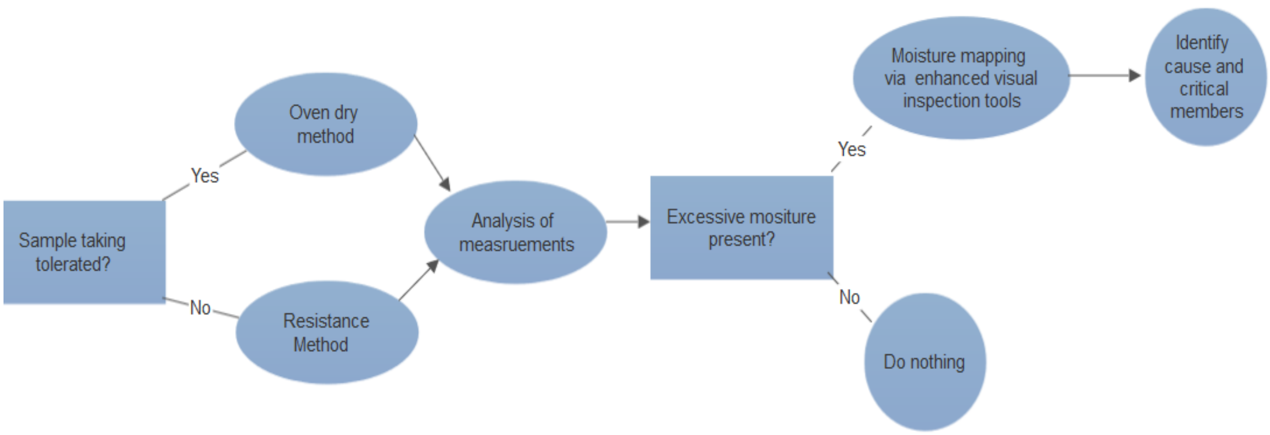


Figure 22 - Decision Path for the Determination of Moisture Content.

5.4 Structural Member Inspection

5.4.1 Input

Subsequently the standard requires that all structural elements are investigated and their dimensions, deformations, growth characteristics, defects, damages and decay/deterioration are documented as well as divided into critical areas. For surface and surface-near saliences visual inspection can be used and supporting equipment such as flashlight, measuring tools, portable ladder and markers should be brought along for proper visibility and reachability. However, for interior characteristics, enhanced visual equipment is needed and if semi-destructive testing is tolerated, resistance drilling should be implemented.

5.4.2 Phase

Localization and Geometry

For the dimensioning of structural members, one needs to distinguish between elements that are completely accessible and those that are plastered or imbedded partially or completely in walls, floors and ceilings. For the last cases, the application of an enhanced visual inspection tool is inevitable. One very powerful tool is the ground penetrating radar (GPR) as the technique only requires one-sided access and can distinguish between material interfaces of different dielectric constants. Additionally, the GPR offers the advantage of fast measuring large areas such as floors or walls, where the exact location of wooden elements is not known. This can be seen in graphic below, where GPR was able to detect the location of beams. However, if the dimensions of elements are unknown, the frequency of the GPR could require adjustment for better resolution or penetration depth. In any case, the operator should draw a grid on the element or wall/floor to be sure that everything was scanned and to be able to locate the results to a certain point.

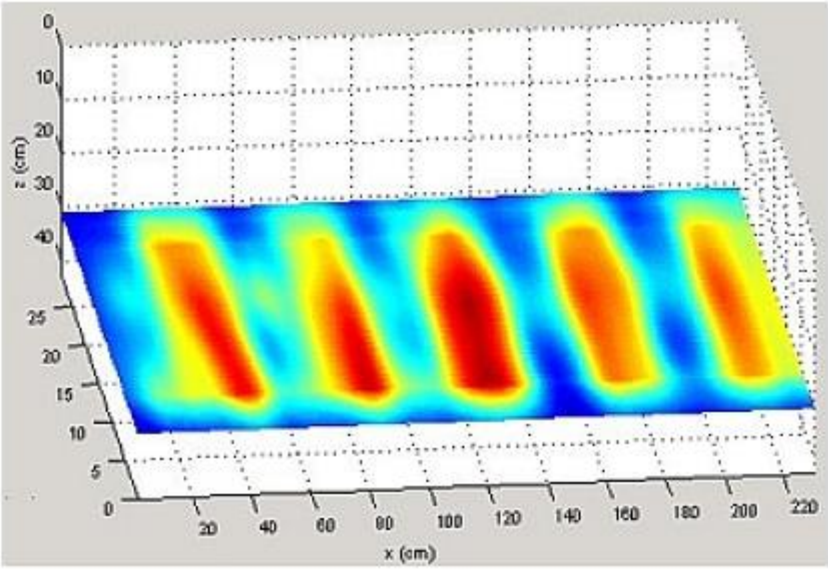


Figure 23 – Location of Beams Found Through the Use of Ground Penetrating Radar (Hasenstab, 2006).

Another technique applicable for the detection or measurement of plastered wooden elements with only one-sided access is active thermography as it is able to highlight different materials due to their diverging cooling behavior. However, it is limited to surface and surface-near areas and therefore only applicable to a certain extend. For elements with two-sided access the radioscopy could be used as it allows clear differentiation between different materials by adjusting the emitted energy. Thereby, low energy beams with a small range of wavelengths are able to penetrate porous materials like wood but would be absorbed by denser materials like concrete or stone. However, if two opposing sides of an element are accessible, the GPR again proves to be superior as a metal plate can be added to the backside which clearly defines the end of an element.

Besides enhanced visual inspection tools, one technique can be applied if semi-destructive testing is approved. In that case, resistance drilling is a very useful tool as it can be used to determine the thickness and shape of an element and in general is able to confirm the findings of the enhanced visual tools used before.

The table below summarizes the described techniques and gives basic recommendations on their procedure:

Technique	Basic Principle	Main output	Recommendations
Thermography	Detection of temperature distribution on surfaces and surface-near areas based on the emitted infrared radiation.	Discovery of different materials/elements and their thicknesses under plaster.	Use of active thermography if natural heat exchange is weak; Attenuation of anomalous heat sources (lamps, heaters); Acquisition of both photographic and thermal images
Radioscopy	Analysis of taken images through one or more planes based on the resulting absorption levels.	Discovery of different materials/elements and their thicknesses under plaster.	Safety regulations have highest priority. Images should be taken without personnel near the operational area. Use of enhancement software for better interpretation of results. Distance of radiation unit to element: 0.5m - 1m.
Radar Scanning	Analysis of travelling behavior of electromagnetic waves that penetrated an element based on the effect of changing interfaces with various dielectric constants.	Discovery of different materials/elements and their thicknesses under plaster.	Design and implementation of measuring grid to ensure complete or maximum possible coverage. Carefully documentation and labeling of every measurement point to avoid errors.
Resistance Drilling	Analysis of the encountered resistance of the drill at a certain depth.	Confirmation of findings from enhanced visual inspection tools. Information about dimension and borders of hidden/plastered elements.	Keep Drill perpendicular to the surface and advance steadily with constant rotation speed. Carefully label each drill to avoid mix-ups. Avoid use if metal objects lie within drilling path.

Table 4 - Techniques for Localization and Geometry of Hidden/Plastered Elements.

Surface and Interior Characteristics

When it comes to the detection of interior damages or defects the GPR is applicable as well but only to a certain limit and inferior for some characteristics, compared to other non-destructive techniques. While it is applicable to find defects such as rots, excessive moisture, voids or external elements, fine defects such as small cracks or knots are hard to detect. Hence, for the detection of interior characteristics other techniques such as ultrasonic scans, radioscopy or thermography are superior. Most beneficial seems to be ultrasonic scans as they have the advantage to be applicable even for elements with one-sided access due to the echo technique. Thereby, ultrasonic waves will be reflected by obstacles such as cracks that lie within their path, or when none are present by the back wall. One-sided reachable elements can also be investigated, using active thermography. As mentioned before, this technique allows only to detect saliences close to the surface, however, these can include cracks or knots that often do not stretch in a straight line but are shifting sideways. Therefore, these kinds of defects and their direction as well as rough dimension can be detected as long as they are located close enough to the surface.

In the case that opposing sides are accessible, the ultrasonic through-transmission can be used as well as radioscopy. The main advantage of the ultrasonic through-transmission towards radioscopy is that results can be visualized in 3D and it is capable of detecting even thin defects. Additionally, it is possible to detect rotten or decayed areas as the velocity of ultrasonic waves will decrease. When using the through-transmission, one must make sure that the positioning of transmitter and receiver is exact and that the thickness of the measured plane is known as the used frequency will be based on the shortest distance between the two. Problematic with the ultrasonic through-transmission is that it can be hard to distinguish between one large or several small defects, if they are close together. Furthermore, both ultrasonic techniques are not usable if the surface is rotten or cracked parallel to the surface and if the surface's roughness exceeds 5mm.

Radioscopy on the other hand is not influenced by surface conditions, yet, has the disadvantage that one scan only represents a plane in two dimensions. Therefore, small defects are only detectable if they are not smaller than 2% of the member thickness and are not perpendicular to the penetrated plane. Thus, it is beneficial to perform scans from different sides of the element or at least different angles, if possible. The main advantage of radioscopy is that its captured images are in a high definition allowing to detect thin defects such as insect decay or small knots and even individual growth rings. This feature is highly beneficial for the requirements set by the standard as it allows differentiation between the type of defect and also indicates the size and direction of it. However, one must keep in mind safety aspects when using radioscopy as radiation energy is not to be underestimated in terms of impact on human health.

Although not required by the standard, the connections of a structure should be investigated as well since they are regularly done with objects of different materials, for example nails and therefore often not visible to the bare eye. Through enhanced visual inspection tools such as radioscopy, one is able to investigate types of joints and the quality of the material used for those connections. Since these connections are often not visible to the bare eye, their investigation is of great importance.

For a reliable assurance of the findings from scanning techniques, discussed above, the Resistograph or resistance drilling offers an easy, yet semi-destructive solution. Through this method, one can accurately examine the kind of defect or irregularity that was indicated by scans from radioscopy, ultrasonic measurements or GPR. From these scans, the location of saliences is known and their type can be verified using resistance drilling. However, not only the type can be identified through analyzing the encountered resistance but also the dimensions can be learned as the Resistograph records the resistance over depth. Especially, when radioscopy was used but only in one plane due to accessibility, the resistance drill allows to map the findings in terms of their dimension. Thereby, the handling of the drill is vital as it needs to be held constantly and perpendicular towards the penetrated surface, otherwise, the information of depth might be distorted. Additionally, it is important to keep a constant drill rotation and advance for accurate results. Nonetheless, one needs to consider carefully on whether or not resistance drilling should be used when working with structures of cultural heritage as it is a semi-destructive technique. In some cases, it might even be unnecessary to use resistance drilling, if information gained from other non-destructive techniques is already sufficient enough to make reliable assessments on the structure's stability and material quality.

The following table summarizes the described techniques and gives basic recommendations on their procedure:

Technique	Basic Principle	Main output	Recommendations
Ultrasonic Testing	Analysis of behavior of ultrasonic waves that penetrate an element based on the effect of barriers in the wave path.	Detection of irregularities or foreign objects within the investigated element.	Use of coupling agent for better transmission. Equal positioning of transmitter and receiver (through transmission method). Several impulses per measuring point to avoid errors
Radioscopy	Analysis of taken images through one or more planes based on the resulting absorption levels.	Detection of irregularities or foreign objects within the investigated element.	Safety regulations have highest priority. Images should be taken without personnel near the operational area. Use of enhancement software for better interpretation of results. Distance to element: 0.5m - 1m. Irregularities of less than 2% of total thickness are hard to discover.
Radar Scanning	Analysis of travelling behavior of electromagnetic waves that penetrated an element based on the effect of changing interfaces with various dielectric constants.	Detection of irregularities or foreign objects within the investigated element.	Design and implementation of measuring grid to ensure complete or maximum possible coverage. Carefully documentation and labeling of every measurement point to avoid errors. Several impulses per measuring point to avoid errors.
Resistance Drilling	Analysis of the encountered resistance of the drill at a certain depth.	Confirmation of findings from enhanced visual inspections tools. Detection of position and size of irregularities or foreign objects.	Keep Drill perpendicular to the surface and advance steadily with constant rotation speed. Carefully label each drill to avoid mix-ups. Avoid use if metal objects lie within drilling path.

Table 5 – Techniques for Analysis of Interior Characteristics.

5.4.3 Expected Results

The results from the structural member investigation yield information on the geometry, location, surface and interior characteristics of the structural members. All of this information is required by the standard and the individual members can be assigned with an operational category using the tables provided by the standard. Depending on the operational category and species, each investigated member can be classified in terms of their mechanical strength. Therefore, the inspector is able to evaluate the overall stability of the structure and whether or not it is safe or in need of interventions.

Besides the categorization of members through the standard and their material quality, one is also able to investigate the joints of a structure. This can be very useful as connections in wooden structure are often made out of metal, for instance nails or bolts, that can have a noticeable effect on the structure as they could be corroded. Especially, when excessive moisture is measured this is step that should be performed in order to reliably assess the structure.

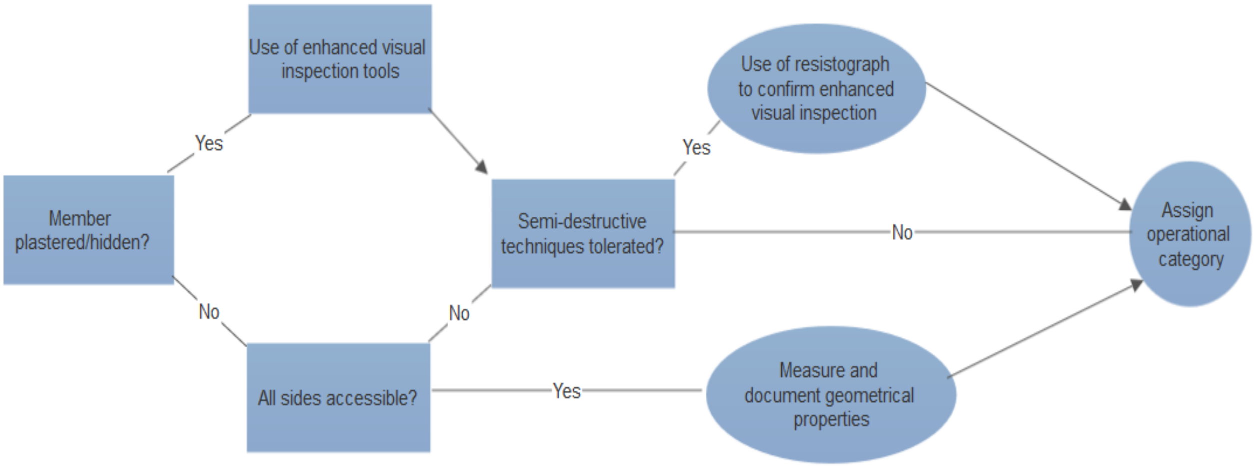


Figure 24 - Decision Path for the Inspection of Structural Members.

5.5 Additional Useful Applications

With the above-described techniques, the standard's requirements can be satisfied and the individual structural elements can be classified using the tables, provided by the standard. However, other parameters that are not regarded by this standard can be found out using the described non-destructive techniques, implemented in this study.

One of these parameters is the dynamic modulus of elasticity (MOE) that can be determined by stress wave measurements like the ultrasonic methods as several studies concluded (Palaia, et al., 2008; Morales Conde, Rodriguez Linan, & Rubio de Hita, 2014). Thereby, one must know the density of the wood species as well as the velocity of the ultrasonic waves. By using the following formula, one can calculate the dynamic modulus of elasticity:

$$MOE = v^2 * \rho$$

$$MOE = \left[\frac{m^2}{s^2}\right] * \left[\frac{kg}{m^3}\right] = \left[\frac{kg}{ms^2}\right] = [N]$$

With

V= Velocity of stress wave [m/s]

ρ = Density of material [kg/m^3]

The modulus of elasticity indicates the resistance of a material towards elastic deformation and can therefore be used to estimate the overall stability of an element or whole structure. Calculations using the above formula could be compared to known modulus of elasticity values of the same species to see if a loss of stability is given.

Another useful parameter that can be estimated using NDT's is density. Several studies (Rinn, Schweingruber, & Schär, 1996; Löwenmark, 2009) have used radioscopy to make estimations on the density of wood by analyzing the greyscale of radiographic images. The greyscale changes with different densities and although studies delivered satisfying results with accuracies of up 97% (Lechner, 2013), no verified procedure is available. Therefore, density values can only be predicted using radioscopy and taking into account the influence of element thickness and moisture content. Additionally, special software and expertise is required to estimate density values from radiographic images.

Average density values can also be estimated using the Resistograph. Thereby, the area defined by the relative resistance diagram is integrated and divided by the depth of penetration to obtain the resistance measure. This allows estimations on the materials as long as the moisture content and the drills characteristics are known. Again, this procedure is not harmonized and can therefore be only used for estimations.

Another useful step that can be implemented into an assessment is to identify the biological risk class that is defined by the standard EN 335: 2013 "Durability of wood and wood-based products - Use classes: definitions, application to solid wood and wood-based products". This standard divides structures into different usage classes depending on their use-situation and assigns each class with a risk of biological decay from fungi and insect. This could be done during the visual inspection and helps to plan the further approach as either less or special attention is paid to the investigation of biological risk.

5.6 Procedure Recommendations

The above mentioned non- and semi-destructive tools have to be operated in the right fashion to receive accurate and reliable results. In the following, summarized recommendations on the individual procedures are given.

5.6.1 Resistance Method

- The equipment is switched on and the setting is adjusted to the electrical resistance of the investigated species.
- Length and isolation type of the electrodes are chosen according to assessment requirements.
- The first measurement should be performed in an area without signs of excessive moisture or other irregularities, in order to measure the usual moisture content of the investigated element.
- When the test is started, it is vital that the angle of penetration is perpendicular as it allows to connect the measurement to a certain depth.
- Once the electrodes are driven into the element, the operator should leave the equipment to level out until the reading is set.
- The test should be repeated at different locations and depths to receive information for the whole element.
- A good practice is to turn off the equipment after every reading as to avoid influence from prior measurements.

5.6.2 Ultrasonic Testing

- Before the test starts, the operator must be sure that the element is not plastered or does not have a roughness exceeding 5mm to assure a successful penetration by the ultrasonic waves. Additionally, the surface cannot be rotten and the element must be free of cracks parallel to the surface.
- When the through-transmission method is used, two opposing sides of the element are required.
- When the echo-method is used, the penetration depth is limited to a maximum of 1m (BAM, 2004).
- For both methods, the thickness of the element needs to be known as the frequency of the emitted waves is adjusted to it and resulting velocities are calculated through it.
- Similar, both methods require a measurement grid which should be drawn onto the element and assures a complete scan. Additionally, the results of the scan can be connected to certain locations.
- When the through-transmission is applied, transmitter and receiver should be positioned equally on opposing sides and perpendicular to the surface to have a minimum distance between them. This allows more accurate results as the wave’s direction of travel is straight. Additionally, coupling agent should be applied to the transmitter and receiver in order to prevent reflections form the wood/air interface.
- For higher accuracy and to eliminate errors, each point of measurement should include several impulses.

- If accessible, all sides of an element should be scanned in order to detect all irregularities as they might be in line with the testing direction and also to see the alignment of fibers and the respective differences in velocity.
- After every point of measurement, the history of results needs to be saved and then cleared to avoid mix-up's.
- When saving the results, the operator must be sure to include element number, measurement point and test direction to be able to identify each measurement afterwards.
- For the post processing, additional software is usually applied where exact thicknesses can be implemented to receive more accurate velocities.
- If irregularities were encountered yet require further tests to identify type and size, the operator should mark and label the position on the element for following measurements.
- A good practice is to document the scan from the starting point and for each measurement point photographically to avoid data loss and as an additional information for the report. This is also very useful if experiments have to be repeated as it improves the accuracy of the repletion.

5.6.3 Radioscopy

Since Thermograph was not practiced first hand in laboratory, the following recommendations were taken from other studies (Löwenmark, 2009; Pincu & Kleinberger-Riedrich, 2011).

- Before the test starts, the operator must ensure that accessibility to opposing sides of the element is given. Additionally, it must be ensured that all safety measures are implemented and that all involved personnel are following these regulations.
- The distance between the investigated object and the X-ray generator should be between 50cm and 1m. The image plate should be positioned as close to the back wall of the object as possible and fastened so that it stays in position.
- When digital radioscopy equipment is used, images can be taken within seconds and results are usually visualized by the supporting computer immediately. Therefore, unsatisfactory images can be repeated within short time. The image taking can normally be done through a starting button and therefore no one should be close to the operational area during that process for health and safety reasons.
- Most modern equipment comes with sharpening tools that are able to enhance the quality of the taken images noticeably and ease the interpretation of results.
- If irregularities were encountered yet require further tests to identify type and size, the operator should mark and label the position on the element for following measurements.
- A good practice is to document the scan from the starting point and for each measurement point photographically to avoid data loss and as an additional information for the report. This is also very useful if experiments have to be repeated as it improves the accuracy of the repletion.

5.6.4 Thermography

Since Thermograph was not practiced first hand in laboratory, the following recommendations were taken from other studies (BAM, 2004).

- If a heating source is necessary, it should be placed within 10cm to 20cm to the investigated surface. Furthermore, the operator must assure that no external radiation source is present and avoid other influences like wind or dust.
- The heating should be done in a constant manner and the operator must assure a power supply for the heating unit.
- The infrared camera should be positioned at least two meters away from the object to capture its whole size. Additionally, the camera needs to be fixed in its position and should be switched on at least half an hour before the start of testing.
- Depending on the situation the operator must select an appropriate objective for the camera.
- Before the test starts, it is a good practice to perform an operational test on a reference object with known surface temperature, to assure the functionality of the equipment.
- The start of testing begins with the end of heating and therefore the camera should be turned on during the heating process in order to record the immediate cooling behavior of the object's surface.
- While the camera is recording the operator has to make sure that the camera has clear vision on the object and that nothing or no one is entering the space in between.
- If irregularities were encountered yet require further tests to identify type and size, the operator should mark and label the position on the element for following measurements.
- A good practice is to document the scan from the starting point and for each measurement point photographically to avoid data loss and as an additional information for the report. This is also very useful if experiments have to be repeated as it improves the accuracy of the repletion.

5.6.5 Radar Scanning

Since Thermograph was not practiced first hand in laboratory, the following recommendations were taken from other studies (BAM, 2004).

- A good practice is to have at least two persons that perform radar scans, one in control of the radar unit, the other relocating the antenna.
- Before the test starts, antennas should be chosen with respect to the elements thickness and turned on a few minutes in advance to stabilize their performance. Thereby, low frequency antennas are most useful for thick elements and high frequency ones for thicker objects. A good practice is to perform preliminary test in order to find the best resolution for a certain thickness.
- The operator should carefully consider the geometric conditions and perform scans from every accessible side. A grid should be designed that covers the whole area of interest, especially for scans of walls or roofs/floors where complete coverage is not possible.
- When the grid is prepared, the operator needs to ensure that the grid-lines are followed accurately and that the exact position of measurements is monitored. Thereby, each measurement point should include direction and length of the investigated profile as well as the orientation of the antenna.

- Saliences in form of metal objects or surface moisture should be observed and documented as they can alter the results and if missed can cause confusion during the data interpretation.
- If irregularities were encountered yet require further tests to identify type and size, the operator should mark and label the position on the element for following measurements.
- A good practice is to document the scan from the starting point and for each measurement point photographically to avoid data loss and as an additional information for the report. This is also very useful if experiments have to be repeated as it improves the accuracy of the repletion.

5.6.6 Resistance Drilling (Resistograph)

- Prior to the start of testing, the respective measurement needs to be labeled with element number, position, and direction of testing.
- The drill needs to be fully reversed and set to clockwise rotation before the test is commenced.
- The operator needs to apply the drill perpendicular to the surface and keep this position in order to connect the encountered resistance to a certain depth.
- When drilling, the rotation speed and advance of the drill have to be constant.
- Once the back wall or desired depth is reached, the drill has to be set to counterclockwise and is to be removed in a straight and slow manner so that the borehole is not extended. The rotation speed can thereby be high.

6. Use of NDT in Laboratory

Some available non-destructive techniques were tested in laboratory to become familiar with their setup, procedure and post-processing. The tests were carried out on pine and fir samples and included visual inspection, moisture content measurements, Resistograph/resistance drilling and ultrasonic through-transmission. A laboratory report of the performed tests can be found in the appendix.

7. Conclusions and Future Research

Several aspects and advantages of non-destructive testing have been observed during this study. Thereby, not only the benefits of individual techniques were acknowledged but also the importance of combining different techniques to confirm and review the results of one another. However, it was also learned that there are only a few standards and codes addressing the field of non-destructive assessments and the correlated procedures which have been criticized by some (Löwenmark, 2009; Rug, 2014; Tannert, et al., 2010).

The benefits of non-destructive testing and combined use of techniques were experienced first-hand during the laboratory work, where saliences from the visual inspection were confirmed by the results of resistance drilling and ultrasonic measurements. Additionally, the handy, easy to use and fast to repeat procedure of the different methods was recognized, which enables them perfectly for in-situ testing.

Also, techniques, aside the ones used in the laboratory, were investigated theoretically and evaluated in their potential to satisfy the available Italian standard UNI 11119. The different techniques were analyzed for the respective requirements set by the standard and balanced against one another. The following conclusions were drawn from this comparison:

- Moisture content can be measured fast and easily through the resistance method without damaging the element majorly. For a verification of the results and for the mapping of moisture additional techniques can be implemented with resistance drilling, thermography, GPR and radioscopy.

- The problem that elements that are in parts or completely covered by plaster and are therefore not measurable or detectable without supporting tools, can be solved by using the ground-penetrating radar. It is applicable with only one-sided access, tolerates also rough surfaces and can be used to fast scan entire areas for the location and dimension of beams or columns. For the detection and location of structural elements, thermography can be used as well and it is even superior towards the GPR as it can be used when metal objects prevent the use of GPR. However, it is limited to a certain depth and therefore might not be able to dimension the element over its complete thickness. This limitation could be solved using the Resistograph in order to measure the element's thickness.

- When analyzing the inner structure of an element, the accessibility plays as vital role. For one-sided access, the ultrasonic echo method can be seen superior towards the GPR as it is able to detect also thin defects. Active thermography can also be used in this case, yet it only provides information to a depth of about 5 cm. For the case of two opposing sides, the ultrasonic through-transmission is applicable and especially for thick elements it outdoes the echo method. However, radioscopy proves to be at least equal as is able to produce images in high resolution, showing even the different growth rings. Problematic on the other hand is that the images are only in 2D and an ideal use of radioscopy would require access from at least three sides. Yet, for this case the Resistograph proves its worth as it can provide information on the dimension of salience that were discovered by radioscopy. In general, resistance drilling is a powerful tool for the verification of results from enhanced visual inspection techniques. However, being a semi-destructive technique, its use might not be desired in structures of cultural heritage.

- Additional information that is not required by the standard includes the estimation of the modulus of elasticity and density. Ultrasonic measurements offer to calculate the modulus of elasticity while radioscopy and resistance drilling allow estimations on density. Both properties offer vital information on stability, yet, estimations based on these techniques are not harmonized or officially recognized and should therefore only be implemented for comparative reasons and predictions on material strength.

The developed guideline/best practice is not a ground-breaking step for non-destructive testing and being focused on only one standard it is not ideal for harmonized use. However, the reviewed standards and guideline of this dissertation, are implementing investigative procedures and steps that are referring to the use of non-destructive techniques, mainly for preliminary checks/investigations. Often missing thereby is the recommendation on the proper technique for different situations and requirements. Therefore, the produced guideline can be seen as a useful addition to these standards and as a step further to the establishment of non-destructive techniques as a recognized assessment method. Moreover, non-destructive diagnostics are not only limited to old or historic structures but can also be applied to recently constructed ones as wood is always a target for decay and deterioration from external causes.

Especially, the potential of this sort of assessment in terms of ecological and economic benefits (Morales Conde, et al., 2014) is noteworthy and should be of great interest for stakeholders. Non-destructive techniques often do not require a high expertise for their use and can be applied without disturbing the structure's stability in any way. Therefore, they are predestinated for periodical checks that can be implemented as a part of maintenance and allow early detection of strength diminishing influences. Furthermore, if these influences are already present, non-destructive techniques offer to distinguish between sound and damaged timber. Both beneficial applications will reduce the amount of interventions thus lowering the amount of construction work, material used and costs raised.

Nowadays, the importance of sustainable construction is more and more recognized and therefore sustainable materials such as wood are becoming more popular. Like others before (Löwenmark, 2009; Rug, 2014; Tannert, et al., 2010) this study calls for further research on the individual techniques which would include harmonized testing procedures and acknowledge the potential of these methods. This could not only enhance the respective techniques but also open new possibilities if for example strength properties such as modulus of elasticity and density are able to be determined reliably by non-destructive techniques. This is especially interesting for structures of cultural heritage as, sometimes undesirable, semi-destructive techniques like resistance drilling could become obsolete.

Of equal importance is however the development of standards regulating the assessment procedure that are following the example of the national standards from Italy and Switzerland. Although, this call for further standards or studies on non-destructive assessments is anything but new, one must wonder why so little has been done. Especially, if one considers the amount of renovation work for example of Germany that has a major construction industry and where 70-80% of the total construction volume are already related to renovation works (Rug, 2014). Therefore, codes and standards need to be focused not only on historic structures and their conservational assessment but also on recently built ones, which would not only bring down costs but also be another step towards a sustainable construction industry.

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Picture References

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Appendix

Laboratory Report

Contents

1. Introduction 1
2. Experimental Setup 1
2.1 Sample Description 1
2.2 Visual Inspection 2
2.3 Moisture Content 2
2.3.1 Method 2
2.3.2 Used Equipment 3
2.3.3 Procedure Description 3
2.4 Resistograph (Resistance Drilling) 4
2.4.1 Method 4
2.4.2 Used Equipment 4
2.4.3 Procedure Description 5
2.5 Ultrasonic Through-transmission 5
2.5.1 Method 5
2.5.2 Used Equipment 6
2.5.3 Procedure Description 7
3. Results and Discussion 8
3.1 Visual Inspection 8
3.2 Moisture Content 10
3.3 Resistograph 11
3.4 Ultrasonic Through-transmission 13
5. Conclusion 15
Appendix 16

1. Introduction

This laboratory report is an excerpt from the work that was performed for the master study "Non-destructive diagnostics for timber structures in historic buildings: investigation methods and testing tools". It comprises non- and semi-destructive diagnostic techniques such as visual inspection, moisture content measurement, resistance drilling and ultrasonic testing on pine and fir samples. The aim thereby was to become familiar with the techniques and their practical procedure in order to be able to evaluate their applicability, benefits and disadvantages for non-destructive testing. This practical insight is therefore expected to be a helpful action for the assessment of the study that validates individual, non-destructive techniques for their individual and combination use in the assessment of historical buildings. The tests were performed at the Politecnico di Bari under the supervision of Mariella de Fino and Rocco Rubino.

2. Experimental Setup

2.1 Sample Description

For this laboratory procedure, three samples of pine and three samples of fir were used. The fir samples were cubes with a side length of approximately 10cm and the pine samples were cuboids with the dimensions 10x10x5cm. Thereby, the pine samples had one square surface with rills milled into it as it can be seen in the pictures below. All other samples and sample sides are documented in the annex.


Figure 1 & 2 – View of Sample Cross Sections with Pine on the Left and Fir on the Right.

The samples were labeled according to their species and each side was given a letter for identification. The letters A/C therefore showed the cross section with growth rings and tests performed through this plane would be along the direction of fibers. Tests performed through B/D would be tangential to the direction of fibers and tests through E/F would be perpendicular.

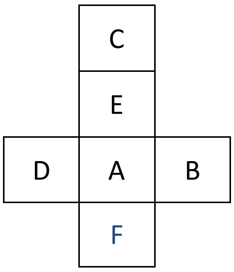


Figure 3 – Schematic of Sample Labeling of an "Opened" Specimen.

2.2 Visual Inspection

All samples were inspected with the bare eye in order to detect defects or irregularities such as cracks or knots. These can have an influence on the results of following tests, especially when they are not limited to the surface but also reach the interior of a sample. The square and milled surfaces of the pine wood samples were thereby disregarded as they were not tested in this laboratory set.

2.3 Moisture Content

2.3.1 Method

The moisture content of the samples was measured using the resistance method. The moisture content is an important property of wood as it can indicate the presence of biological form fungi or insect as these prefer wood with a high moisture content. The resistance method uses a moisture meter that contains two pin-type electrodes, in between which, the electrical resistance is measured to estimate the moisture content. The equipment used in this study was the “Logica LG43” model which contained a small computer system, a gadget for the electrodes and connection cables. The electrodes-holding gadget was also used for driving the electrodes into the wood, using the metal handle as a hammer. Electrodes in this model can be screwed onto the gadget and come in different lengths and isolation type. Before the start of tests, the species of the used samples must be known as the equipment divides different tree species into three groups due to the difference of electrical resistance between species.

Figure 4 – Equipment of the Logica LG43 with Computer, Gadget and Connection Cables (left to right).

2.3.2 Used Equipment

Below, the technical features and endowments of the used Logica LG43 moisture meter can be seen.

Technical features

- Measured range: 8-50%
- Number of woods: 4
- Number of building material loads: 5
- Shelf life: 2
- Temperature indication: -10 / 50C
- Power Battery: 9V 6F22
- Autonomy: 35h Ca.
- Case dimensions: 32,5x26x8 cm
- Case weight: 1,3 - 3,0 - 3,5 Kg Ca
- Thermo-hygrometer mode (with optional RH / T sensor)
- Temperature range: -10 / + 80 ° C
- Temperature accuracy: ± 0.5 (0-40 ° C) ± 1.2 (-20 + 80 ° C)
- Moisture Range: 0-100% RH
- Humidity accuracy: ± 2% (10-90%) ± 4% (0-10%)

Endowment:

- Carrying case
- Probe
- Hammer
- Electrodes
- Clamping key
- Cable
- Alkaline battery
- User manual

Figure 5 – Measuring of Moisture Content of Fir Sample.

2.3.3 Procedure Description

Moisture contents were measured once for each sample with the following procedure:

1. The equipment was connected, the chosen electrodes attached to the gadget and the computer was turned on.
2. Afterwards, the right group was selected. In this case, pine and fir wood samples were used which both belonged to Group 2.
3. To begin the test, an area of sound wood without signs of excessive moisture was chosen. Then the electrodes were placed perpendicular to the surface and driven into the sample using the handle as a hammer.
4. Once the desired depth was reached, the equipment was left to settle and the moisture content (in percent) was read from the display and documented.
5. After each test, the equipment was turned off and the test cycle was repeated. Turning off the equipment is a safety measure used to avoid influences from previous tests.

2.4 Resistograph (Resistance Drilling)

2.4.1 Method

This semi-destructive technique drives a micro-drill into a wooden object and measures the resistance of the material while drilling. Changes in the resistance can be caused by voids, decay or knots where the density of the material changes. When used in-situ, this technique should be used after structural elements have been scanned with other non-destructive techniques such as ultrasonic or radar to confirm the findings of those. The resistance drilling can accurately locate and size interior irregularities of wood but is always dependent on scans that indicated those irregularities before.

For the application in laboratory, the Resistograph was used without previous scans indicating interior irregularities. The aim was to become familiar with the technique as well as its procedure and drills were made to see the different behavior of the drill depending on the direction of fibers. While drilling it is important to hold the drill stable, perpendicular to the surface and advance in a constant matter with constant drill-speed.

The equipment used was from the IML RESI F- Series and its technical features and endowment can be seen below. The results of the drill can be gained digitally as the drill has a slot for an USB memory stick or analogously through a paper resistance diagram that is drawn by the drill during the test. Due to bad experiences with digital results, the analog method was chosen.

The drilling was done three times for fir samples, in grain direction, perpendicular and tangential to it. For the pine samples, drills were only made in tangential direction as the perpendicular direction was disregarded due to the milled surface. The drill in direction of fibers was disregarded as it holds only little information since the drill hardly encounters obstacles, if any.

2.4.2 Used Equipment

Below, the technical features and endowments of the used resistance drill IML RESI F- Series can be seen.

Technical features

- Drilling depths 150mm – 500mm
- Lithium-Ion rechargeable battery
- Feed speed with 2 stages up to 150 cm/min
- 2 sensibility stages for hard and soft wood
- Bluetooth electronic unit for rapid digital acquisition of measurement data
- 2 gear selections of 400/1200 rpm (rounds per minute)

Endowment

- Wax paper stripes
- Drilling needles
- Shoulder strap set
- Bosch accumulator drill GSR 12 V
- 2 storage batteries 12V; 2,0 AhNiCd
- Battery charger AL60 DV 1419
- Drilling attachment IML-RESI F-series with paper magazine
- Transport case

2.4.3 Procedure Description

The procedure for the Resistograph was as follows:

1. The middle of the sample’s surface was marked with a dot, showing the starting point of drilling.
2. The resistance diagram paper was labeled, indicating species, sample number as well as penetrated surfaces and was carefully put in its place.
3. The drill was reset, placed on the starting point perpendicular to the surface and drilling was set to clockwise.
4. Drilling was started with a constant rotation speed and advance, making sure that the drill remained in a stable position.
5. Once the drill penetrated the back wall of the sample, the drilling was stopped, set to counterclockwise and retrieved with a slow advance but high rotation speed.
6. Lastly, the resistance diagram sheet was removed and placed on top of the sample and recorded via photograph while showing the drilling path with the correlated resistance.

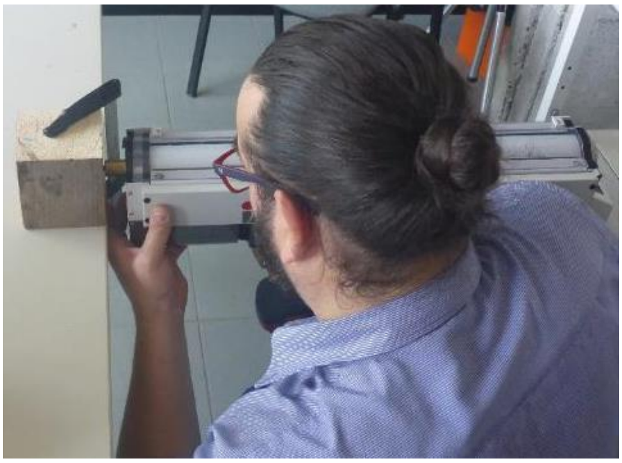


Figure 6 – Resistance Drill in Use.

2.5 Ultrasonic Through-transmission

2.5.1 Method

The ultrasonic through-transmission method is able to detect interior inhomogeneities or defects by sending ultrasonic impulses through an element and recording the time the ultrasonic wave needs to pass the element. Therefore, this technique requires two-sided access to the investigated element as transmitter and receiver of the impulses need to be on opposing sides. From the travel time, the velocity of an impulse can be measured if the thickness of the element is known. However, if an obstacle such as a crack or knot lies within the direct path, the waves will have to encircle it thus, their transition time increases and velocity decreases.

The used ultrasonic system consisted of an ultrasonic unit, a computer system for live data recording, a transmitter, a receiver and a coupling agent. Thereby, the transmitter was attached with a conical to concentrate the transmitted impulses. The coupling agent, a water-based gel, needs to be applied as it helps the ultrasonic waves to overcome the impedance of the wood/air interface and prevents them to be reflected from this interface.

Before the test, the thickness of the tested plane needed to be known roughly and was entered in the computer system which then chooses the configuration of the wave automatically. After the testing, all samples were measured accurately and the dimensions were used with a computer software for the results. Each sample was tested with the ultrasonic technique. Thereby, the fir samples were tested in all three directions; in grain direction, perpendicular and tangential to it. The pine sample were only tested tangential and with fiber orientation due to the milled surface. Each test was performed with longitudinal waves and five impulses were transmitted for each measurement.

Figure 7 – Ultrasonic Equipment with Bottle of Coupling Agent.

2.5.2 Used Equipment

Below, the technical features of the used equipment, Boviar CMS 3.1, can be seen.

Technical features

- 12-bit converter; full-scale ± 2,5 volts
- Amplification 20, 40, 74 dB
- Frequency of 50 kHz to 1,25 MHz
- Acquisition buffer from 0,8ms to 100ms (800ms optional)
- 500mA power supply and battery charge
- Internal 12 V 3.2 Ah battery

Endowment

- Ultrasonic unit with computer control pad
- TSG Ultrasonic transmitter 55 kHz
- TSG Ultrasonic receiver 20 kHz
- Connection cables
- Attachments for signal concentration
- Coupling agent

2.5.3 Procedure Description

Procedure:

1. The equipment was connected, turned on and the sample thickness was entered into the computer.
2. The receiver surface was applied with some coupling agent and the sample was placed centrically on top of the receiver.
3. Coupling agent was applied to the tip of the transmitter and it was placed in the middle of the sample's top surface.
4. Once the transmitter was placed, the ultrasonic unit was turned on and started sending impulses.
5. Through the computer, the live data can be seen and after five impulses the ultrasonic unit was turned off again.
6. The results of the 5 impulses were saved, labeling species, sample number and test direction.
7. After the results were saved, the history of results was cleared and the next test began, repeating the procedure.

Figure 8 – Experimental Setup of Ultrasonic Test.

3. Results and Discussion

3.1 Visual Inspection

Pine sample 1

The sample showed no strong signs of defects or irregularities, however, the surfaces A and C that show the cross section of the tree, appeared to be more porous on the outer sapwood area (see figure below). Other than that, the D surface showed small cracks in the corner towards the surfaces C and E. The cracks appear to be small and in direction of fiber yet could reach further inside the sample.

Figure 9 – 11 – Sample Surfaces A, C and D (left to right) with Visible, Suspicious Areas Marked.

Pine sample 2

Contrary to the first pine wood sample, the second one showed natural irrgeularities and defects on all but two surfaces (B and F). The E surface showed a large knot that was also present on the surfaces A and D as its orientation was towards these surfaces. The other cross-section surface showed no knot but two cracks, both perpendicular to the orientation of fibers.

Figure 11 – 14 – Sample surfaces E, A, D and C (left to right),

Pine sample 3

The third pine sample only contained one irregularity in form of a knot that spread from the milled D surface to the C surface. Besides that, the other surfaces appeared to be without noticeable characteristics, visible to the bare eye.

Figure 15 & 16 – Samples Surfaces D and C (left to right).

Fir sample 1

Two cracks could be seen on the two-cross section surfaces A and C. The surfaces E and F showed little cracks and knots which are expected not to reach far inside the sample. Small dents were seen on the remaining surface B and D but they seemed not to reach further to the interior.

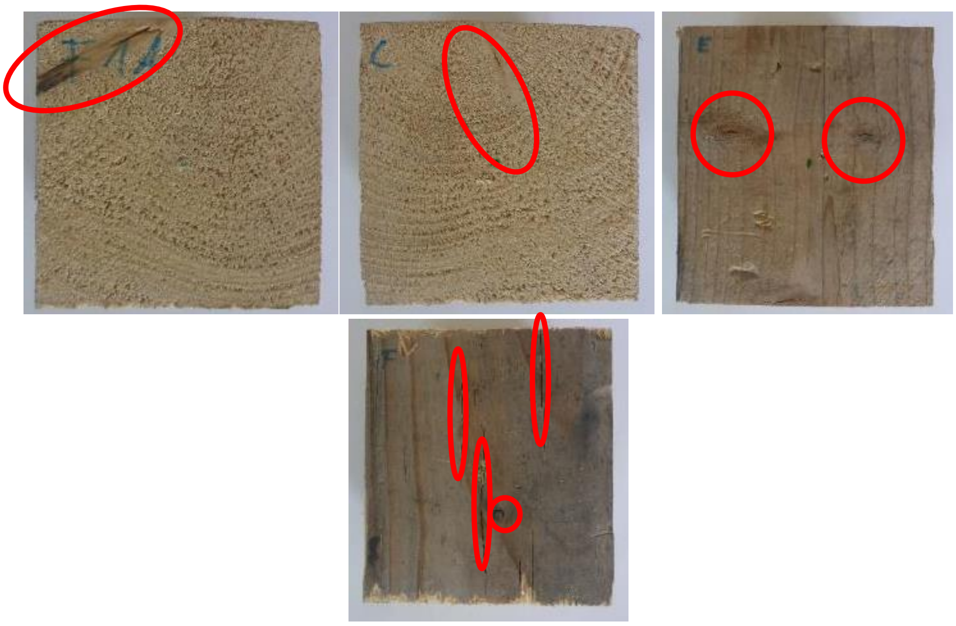


Figure 17-20 – Sample Surfaces A, C, E and F.

Fir sample 2

The second fir sample only showed minor noticeable characteristics. Surfaces D and E contained small knots and surface F had a crack in grain direction. However, due to the small size of all findings, no major effects are expected from these characteristics.

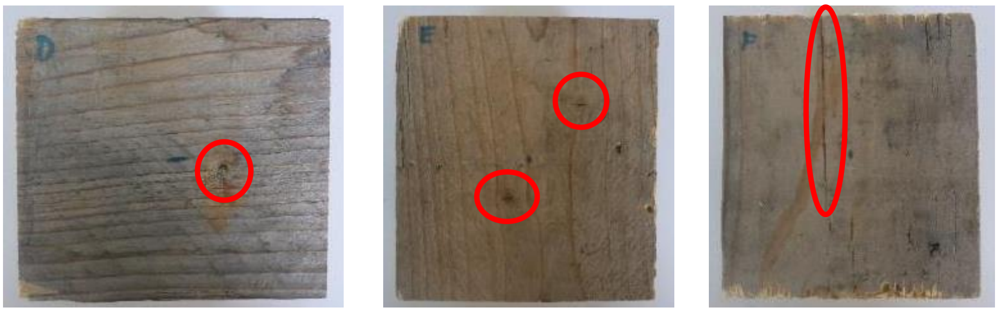


Figure 21-23 – Sample Surfaces D, E and F.

Fir sample 3

Several saliences were found on the surfaces of the last fir sample. Surface A showed a large crack perpendicular to the fiber direction and surfaces B, D and E showed one or several knots. Lastly surface F contained a crack in the direction of grain and reaching almost across the whole length.

Figure 24-28 – Sample Surfaces A, B, D, E, F.

3.2 Moisture Content

The moisture content was measured once per sample with pin electrodes of 2,5 cm and therefore in a depth of about 2cm. As the table below shows, the pine wood samples contained a slightly higher moisture content with 9,2 % on average, with sample P2 measuring the lowest content of 9,1% and sample P1 the highest with 9,3 % respectively. Whereas the fir-wood had an average moisture content of 8,53 %, with measurements of 8,4 % for sample F1 and 8,4% for samples F2 and F3. Thereby, both species showed only little differences in between samples with a range of 0,2% respectively.

Sample	Moisture Content [%]
F1	8,4
F2	8,6
F3	8,6
P1	9,3
P2	9,1
P3	9,2

Table 1 – Moisture Content of All Samples.

3.3 Resistograph

Fir sample 1 A to C

The resistance drilling on the first fir sample was done in grain direction and was therefore expected to encounter only very little resistance since no growth rings would be penetrated. However, as can be seen in the resistance drilling diagram below, the drill encountered three areas of higher density where the resistance amplitude would not fall back to zero. The first section was at a depth of about 0,5cm and approximately 1,5cm long. The second area was at a depth of about 3cm and approximately 1cm long. Lastly, the most noticeable area was met at a depth of about 6cm and was approximately 2,5cm long. Most likely these areas are due to knots that were noticed during the visual inspection and have a higher density than regular wood.

Figure 29 – Resistograph Diagram of Fir Sample 1 with Drilling Direction from Surface A to C.

Fir sample 1 B to D

The second fir sample did not show any irregularities and encountered only little resistance. The resulting graph shows several amplitudes, resulting from the penetration of growth rings in a tangential direction since the drill angle was tangential to the direction of fibers. Two noticeable areas were encountered during drilling where the resistance fell to zero. The first area was at a depth of about 1,5cm and approximately 0,75cm long. The second was met at a depth of about 4,5cm and very small with a length of approximately 0,25cm. Reasons for this loss of resistance could be voids, cracks or areas of decay/deterioration that the drill encountered and where the wood's density is decreased.

Figure 30 - Resistograph Diagram of Fir Sample 1 with Drilling Direction from Surface B to D.

Fir sample 1 E to F

The drilling perpendicular to the direction of fibers showed an expected diagram as shown below. The peak points of the amplitude thereby represent the growth rings that were mostly penetrated in a 90° angle where the resistance is greatest. It is even possible to distinguish between early- and late wood as the late wood was encountered first, resulting in higher resistance peak points. However, besides a typical resistance diagram for perpendicular drilling, one irregularity was encountered by the drill at the far end of the sample. The resistance there increased and only decreased once the drill breached the surface. The encountered resistance was most likely caused by the stretched knot that can be seen in the bottom left corner of the sample in the picture below.

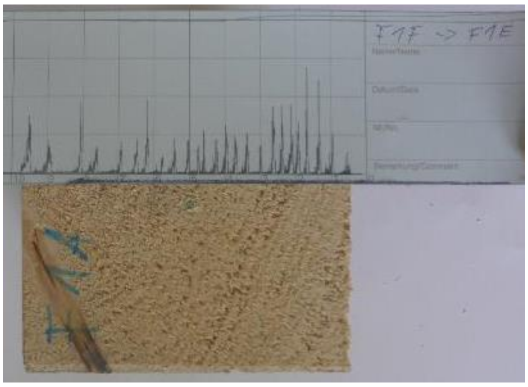


Figure 31 - Resistograph Diagram of Fir Sample 1 with Drilling Direction from Surface F to E.

Pine sample 1 E to F

The first pine sample was drilled through in tangential direction. This can also be seen in the resulting diagram that shows a uniform distribution of resistance. Thereby, the progression of the graph is denser in the beginning where the growth rings were penetrated tangential and therefore more frequently than in the end where the angle was more perpendicular. Additionally, at a depth of about 6cm the resistance does not fall to zero for roughly 2cm. This could be due to an irregularity in form of a little knot, however, none was found on the surface during the visual inspection.

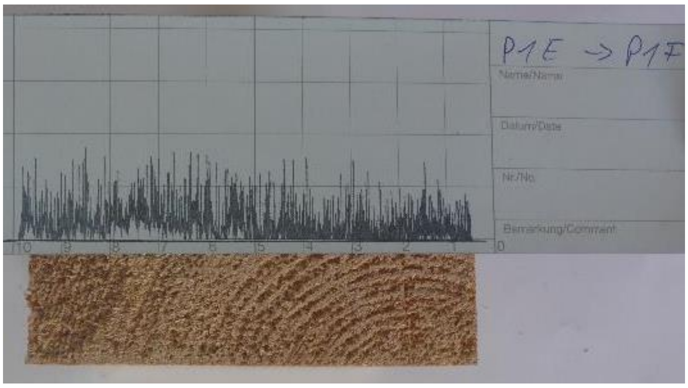


Figure 32 - Resistograph Diagram of Pine sample 1 with Drilling Direction from Surface E to F.

Pine sample 3 E to F

In the case of the third pine sample, the starting point for the drill was not in the center of the surface as it was for the other samples. It was moved approximately 2cm above the center point in order to encounter a knot that was located on the B surface and stretched to the surface C. The resulting diagram showed that the drill met the knot after a depth of about 0,5cm and that it spread sideways over a length of roughly 5,5cm. Other than that, one can see that the drill penetrated the growth rings first in an almost perpendicular angle and later in a more tangential one. This can also be noted as the graphs progression becomes denser when the drill met growth rings more frequently due to the tangential direction.

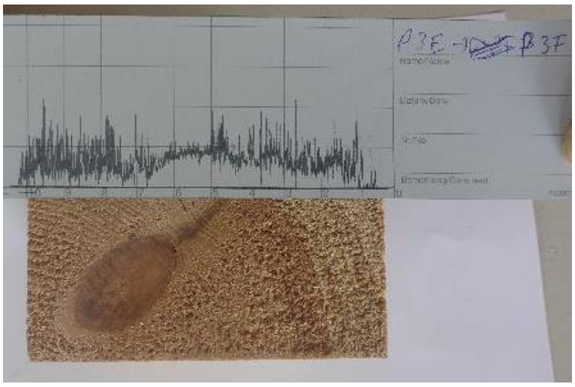


Figure 33 - Resistograph Diagram of Pine Sample 3 with Drilling Direction from Surface E to F.

3.4 Ultrasonic Through-transmission

The first step after the ultrasonic tests were finished, was to measure the thicknesses of the samples accurately which were then used in the post-processing software. For the tests, the thickness was roughly measured and set as 10cm. As it can be seen in the tables below, the measured thicknesses differed up to 1,2cm in case of the second pine sample but was in general below 1cm. The transition time was recorded in microseconds (µs) which corresponds to 1 µs = $1*10^{-6}$ s. Average velocities were calculated as distance over average transition time and given in m/s. Here, a pattern can be noticed, depending on the measured surfaces and the corresponding direction of grain. For instance, the highest velocity was measured when impulses were sent in grain direction, penetrating the plane A-C. The reason for this is that the waves encountered almost no obstacles in form of growth rings for example. Planes B-C and E-F on the other hand, contained growth rings that lied in the path of the waves resulting in higher transition times, thus, lower velocities. Thereby, the lowest velocities were found in perpendicular direction of the fir samples (E-F). For the pine specimen, the perpendicular direction was not measured, thus the tangential was the lowest of the two measured directions.

The three right columns of the table below show the deviation between the impulses of one measurement point. Sigma t thereby represents the deviation in transition time, sigma v in velocity and sigma v % the proportion of the divergence with regards to the average velocity. Thereby, one can note that the deviation in all measurements is only of a few percent or not even present. Divergences can occur when the wood is not completely sound, due to minor systematic errors from the equipment or when the receiver/transmitter is moved slightly which is not preventable when measuring by hand and without fixations. However, since the resulting deviations are that small, they can be neglected.

When one compares the species to one another, it can be noted that the pine samples had a slightly higher velocity in grain direction (A to C) and tangential (E to F) to it. Generally, this means that the pine samples are made out of sounder wood. Additionally, the pine specimen contained smaller widths in their growth rings which, as the graphic below exemplarily shows for spruces, increases the sonic speed. Differences in moisture content where one of the pine samples was seen as slightly higher can have a decreasing effect on sonic speed as well. However, since the pine sample's velocity was higher nonetheless and the difference is too small to have a noticeable effect, this cause was excluded.

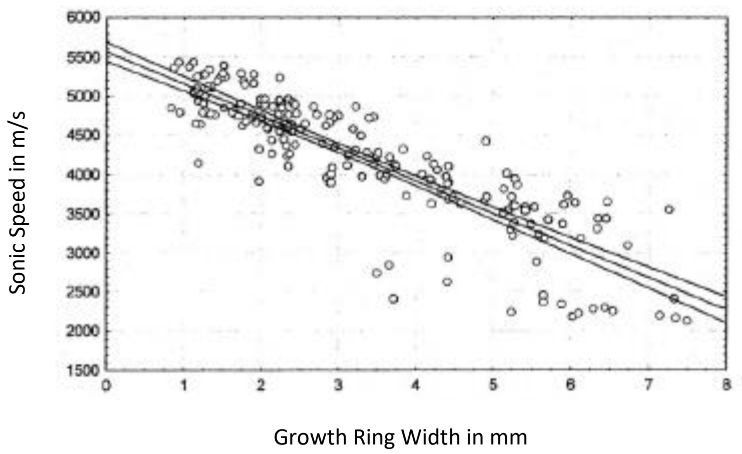


Figure 34 – Influence of Growth Ring Width on Sonic Speed for Spruce (Hasenstab, 2006).

Besides the pine sample's higher velocities, one abnormality can be seen among the fir samples. All measurements in the same direction showed more or less same values of transition time and velocity, only the measurement in grain direction of the first measurement differed. While both other samples in that direction showed velocities well above 5000 m/s with 5434,8 m/s and 5389 m/s for fir samples two and three respectively, the first specimen's average velocity was much lower with 5000 m/s. This indicates either obstacles in the path of the waves or in general low wood quality. However, since the samples were sawed from one wooden element and the measurements in other directions are in line with the two other samples, the lower velocity was probably due to an obstacle. Thereby, it is highly possible that the obstacle was the same that was encountered during the resistance drilling in the same direction and identified as two knots that were noticed during the visual inspection. This would confirm the suspicion that one or both knots proceed through the samples center on the inside thus crossing the path of both, the resistance drill and ultrasonic waves.

Ultrasonic Through-transmission Fir Wood Samples						
Measured surfaces	**Distance (m)**	**Average Transition Time (µs)**	**Average Velocity (m/s)**	**sigma t**	**sigma v**	**sigma v %**
F1AC	0,1	20	5000	0	0	0
F1BD	0,092	65	1416,3	0,4	7,7	0,5
F1EF	0,092	42,4	2169,8	0	0	0
F2AC	0,1	18,4	5434,8	0	0	0
F2BD	0,092	66,2	1390,1	2,1	47,1	3,4
F2EF	0,092	41,9	2194,8	0,4	22,9	1
F3AC	0,1	18,6	5389,5	0,4	101,3	1,9
F3BD	0,092	73,8	1247,3	0,4	6	0,5
F3EF	0,092	40,6	2263,9	0,4	20,2	0,9

Table 2 – Ultrasonic Measurement Results for Fir Samples.

Ultrasonic Through-transmission Pine Wood Samples						
Measured surfaces	**Distance (m)**	**Average Transition Time (µs)**	**Average Velocity (m/s)**	**sigma t**	**sigma v**	**sigma v %**
P1AC	0,1	17,6	5681,8	0	0	0
P1EF	0,094	61,6	1526	0	0	0
P2AC	0,1	17,8	5632,4	0,4	110,5	2
P2EF	0,088	58,1	1515,2	0,4	11,5	0,8
P3AC	0,1	17,6	5681,8	0	0	0
P3EF	0,097	55	1762,4	0,4	11,6	0,7

Table 3 – Ultrasonic Measurement Results of Pine Samples.

5. Conclusion

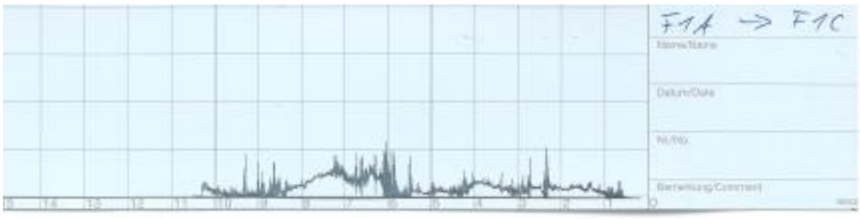
The practical experiences of the laboratory work have been as expected greatly and will be very helpful for the study's evaluation of non-destructive diagnostic techniques. Not only was the knowledge on the individual techniques, their experimental setup and procedure deepened but also the value of combining the results of different techniques in order to understand and explain the behavior of measurements.

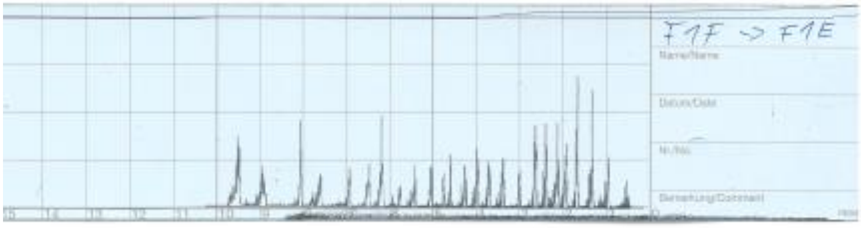
Thereby, the worth of the visual inspection was especially acknowledged as surface and surface-related irregularities or defects showed to have a direct influence on several other testing parameters. For instance, knots detected on the surface during the visual inspection had a noticeable influence during resistance drilling and ultrasonic measurements that allowed conclusions on the interior path of defects without destroying the samples.

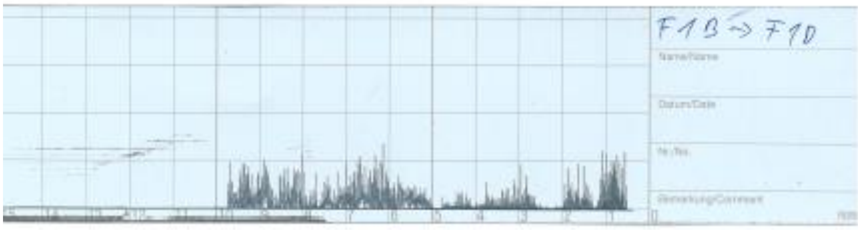
In general, the gained knowledge from the theoretical research part of the study was used for the interpretation of results and increased by setting up, performing and experiencing the respective testing methods as well as analyzing their results. Thereby, the value of non-destructive diagnostic techniques was underpinned as well, since it was possible to see first-hand that relevant parameters and characteristics of wood can be identified and evaluated without damaging samples and in a relatively fast and easy to repeat manner. Of course, since the tests were performed under laboratory conditions and did not include all available or commonly used techniques they can only be seen as a first impression, nonetheless the laboratory experience gave a useful overview on how different techniques are practiced in a correct fashion and compared to one another for accurate and reliable argumentation.

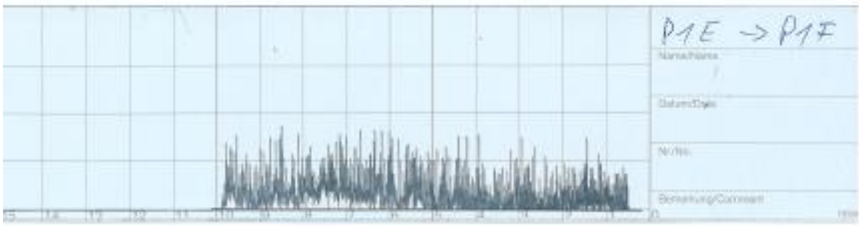
Annex

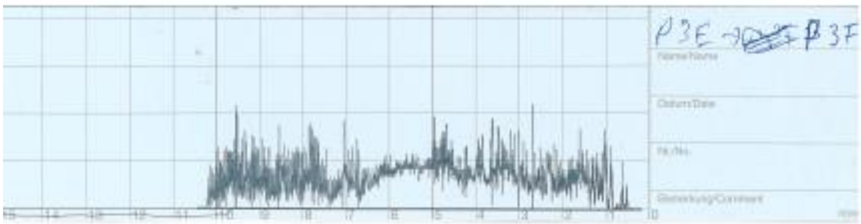
Resistograph Diagram Scans





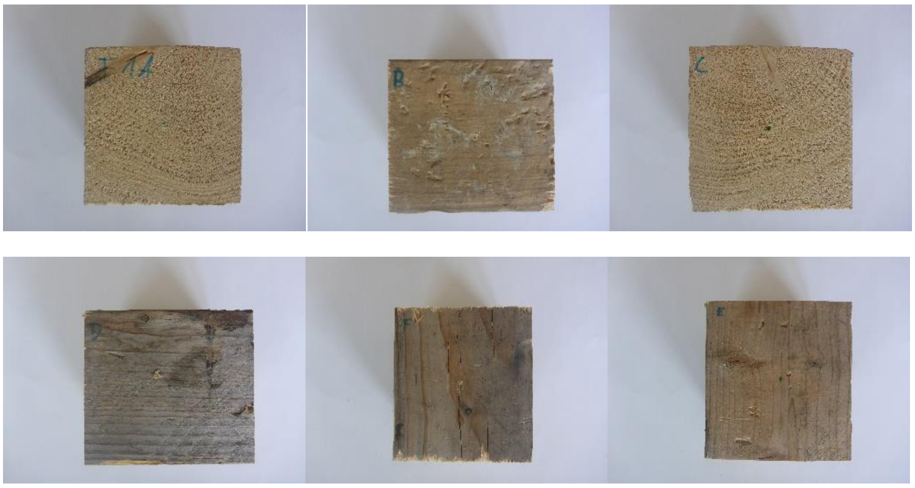






Sample Pictures

Fir sample 1



Fir sample 2

Fir sample 3

Pine sample 1

Pine sample 2

Pine sample 3