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Review

Prediction of mechanical properties by means of semi-destructive methods: A review

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ABSTRACT

Methods and devices for in situ establishment of mechanical properties of wood have been recently developed in cooperation with European, US and Japanese researchers. The development of these new methods was motivated by requirements from engineers who need highly accurate data of mechanical properties of specific elements to plan renovations of historic buildings. Reliable data can replace overly conservative values (usually provided by visual strength grading) in structural analysis, which allows the retention of more original material as the behavior of specific elements is safely assessed. The recently developed methods, which are described in this chapter, are tensile strength of small samples, tensile Young's modulus of mesospecimens, compression strength of cores, compression strength in a drilled hole, mechanical resistance to pin pushing, Young's modulus derived by measuring the hardness and shear strength of screw withdrawals. Although in general the devices for the testing of mechanical properties by the mentioned methods provide more accurate results than the methods used so far, they are not yet mass produced, which should change soon.

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1. Introduction

Several events imply the need to assess the condition of existing timber constructions including their safety and serviceability. For these last purposes a reliable knowledge of the mechanical properties of timber components members is required together with a detailed description of their defects or degradation (strength reduction factors). Acquiring the necessary data by means of destructive tests is generally, impossible for various reasons, namely those related to historical structures [1] or those due to the high variability between members implying the need to test a large number of members which is unaffordable. For all these reasons several non-destructive testing (NDT) methods were developed and used as tools to provide non-invasive condition diagnostics of the wooden material [2]. However, except for proof-loading, NDT methods have only a very limited capacity for predicting the mechanical characteristics of timber structural members due to the relatively poor to medium correlation between the indicative non-destructive parameters and the strength or stiffness of the material. Thus more intrusive methods

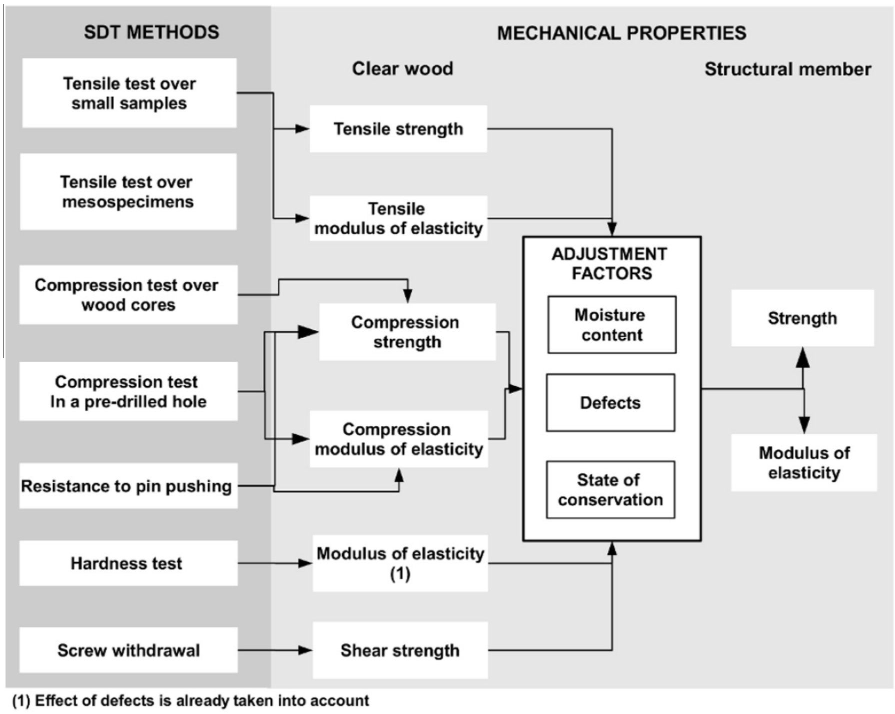


Fig. 1. SDT described in the present paper.

have been developed requiring the removal of a very small sample of material or slight local damage of the structural element which does not affect its global mechanical behavior and therefore does not endanger the safety, stability or durability of the structure. Furthermore, when damage occurs and can affect the visual appearance of the element easy and simple repair techniques can hide the visual impact of the test. Such low invasive methods are usually categorized as moderately destructive testing (MDT) or semi-destructive testing (SDT) methods. The latter term is used in this paper because it is more frequently used in the wood science field. The SDT methods integrate the benefits of both indirect non-destructive and direct destructive testing techniques.

All SDT methods only indicate the properties of clear wood zones present in structural timber members and some of them only describe the mechanical properties at the surface of the element. In order to extrapolate from clear wood to a structural member, the presence of defects (e.g. knots, slope of the grain) and the high spatial variability (across the cross-section and length) have to be taken into account. Among the methods described in the present paper only one method (hardness test) takes the effect of defects into account as part of the method, Fig. 1. The other methods make reference to this necessity, usually by applying a strength reduction factor determined by visual grading or other NDT methods. The critical judgment of defects is left to the expert as part of his own survey procedure methodology for the allocation of mechanical properties to the timber members. Recent guidelines may be used to apply this approach [3] and to use strength reduction factors as usually done for allowable stresses inference [4]. All these SDT tests cannot be seen as standalone methods but instead for reliable predictions it is advised to combine (or compare) the information obtained from two or more methods, including always visual strength grading.

Recent efforts have been made to describe available equipments, application methods, and limitations of SDT methods [2]. The present paper re-examine only those STD methods that provide in situ a direct measurement of strength or stiffness of wood as a response to a mechanical action. Therefore methods used for indirectly making inference about mechanical properties as dynamic pin penetration method (e.g. Pilodyn) [5] and resistance drilling (e.g. Resistograph) [6] are not be described in the present paper.

Seven different SDT methods are described in the present paper along with their working principles, limitations, usual application and general recommendations. A comparison between the different methods are presented considering the representativeness of the results taking into consideration spatial variability (namely the volume of cross-section analyzed), time consumption and extend of intrusiveness (volume of material damaged). For all methods examples of application in situ is presented. All this information intends to provide users with sufficient information about sampling and testing techniques as well as the limits of each method and specific examples of its application.

2. Tensile strength of small samples

2.1. Testing methodology

The assessment of bending strength is important for in situ assessment of timber elements as it is the prevailing manner of loading in e.g. ceiling constructions. Bending strength of integrated timber cannot be established without damage done to the construction. However, it is close to tensile strength and according to some authors it can be considered almost the same [7]. Therefore, a new method to establish strength of integrated timber using small samples taken from its surface was devised.

Samples for the establishment of tensile strength are extracted in a simple way using an adjustable circular saw. Sampling is carried out by two cuts inclined in an angle of 45° in relation to the element surface (Fig. 2) parallel to the grain. The cut depth is adjusted so that a triangular bar with rectangular sides of about 5–8 mm is gained. The saw runs in guides, which are fixed to the surface of a tested element by screws. The damage done to the surface is remedied by insertion of a triangular bar with the same dimensions; it can also be totally mended by restoration. During the production of a sample, the area of the bar section is reduced to about 8–12 mm^2 in the central part, which corresponds to

Fig. 2. Circular saw with guides, modified.

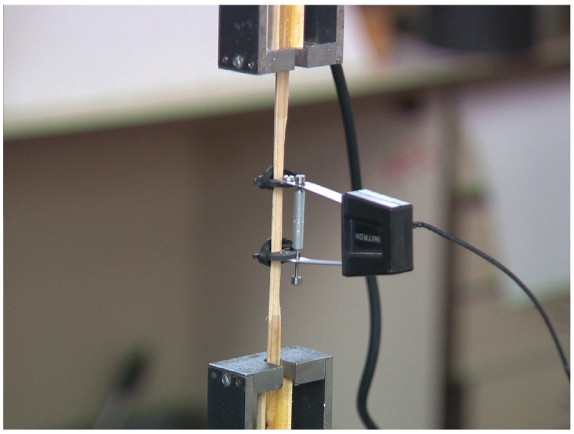


Fig. 3. Tensile test of a triangular bar.

Fig. 4. Truss construction in the former brewery in Děčín.

Fig. 5. A detail of an analyzed beam surface.

production of tensile samples in compliance with [8]. The samples should not contain any natural defects (knots, cracks or other damage). Rectangular wooden blocks are glued to both ends of the samples (Fig. 3) in order to fix the small samples in coaxial articulated grips of the loading device during the tensile strength testing [9].

The tensile sample is inserted in simple grips designed for this purpose and loaded in a common testing device (Fig. 3). The test is not standard but its concept is very close to the standard test in compliance with [8], as it uses the same simple layout eliminating parasite movement and a cross-section with a small number of annual rings. The test measures the tensile strength and the modulus of deformability to calculate the modulus of elasticity. The maximum tensile loading for each sample is the ultimate load and the tensile strength is determined by the formula:

$$f_c = \frac{F_{\max}}{0,5 \cdot bh} \quad [\mathrm{MPa}] \tag{1}$$

where f_t – tensile strength [MPa], $F_{\max}$ – ultimate load [N], b – triangular bar hypotenuse [mm], h – triangular bar height [mm].

The results gained by this test does not need to be correlated and can be declared as similar to that obtained from a small clear wood standard test. For the purpose of the construction safety assessment and dimensioning, mechanical properties established by the described test must be converted to technical properties of timber which take account of the locally measured strength of clean timber reduced by defects that commonly appear in large elements (knots, cracks, and others). The disadvantage of this method is the damage done to the surface of the assessed element, which is undesirable in the case of historic construction timber assessment [10].

Table 1
Mean values of strength and modulus of elasticity from the tests of small tensile samples in the surface (damaged) and inner (undamaged) layers of timber.

Beam side	Tensile tests parallel to the grain			
	Strength S_c [MPa]		Modulus of elasticity *MOE* [MPa]	
	Surface	Inner	Surface	Inner
Top	18.85	47.49	14801.66	12541.10
Bottom	17.52	55.16	16116.45	13957.38
Lateral	20.15	40.86	12444.37	13261.16

2.2. Limitations

The method for the establishment of tensile strength and modulus of elasticity uses small triangular samples that are taken from a relatively shallow part of the surface of a timber element, where the historic timber is often damaged by biotic factors. The method is very sensitive to fiber deflections in the sample and requires a careful choice of a sampling place and careful sampling. The cross-sections of the sample is small, which increases the effect of a higher earlywood proportion. This effect is negligible in larger cross-sections. As a result, the values of strength and modulus of elasticity will be highly variable. Therefore, it is necessary to think well about the places where samples are to be taken and also take account of potential damage.

2.3. Application

The tests of tensile samples have been successfully used e.g. when investigating the quality of ceiling joists in the St. Mary's Tower of the Karlstejn castle or strength values of the storage hall in the trade fair facilities in Brno (South Moravia – CR).

The method can be also used to determine the level of damage to the surface layer of the timber. As an example we can name the study into the effect of fire protection treatment that has been repeatedly applied to timber constructions of historic buildings. The application of agents with fire retardants on the basis of sulfate and ammonium phosphate has caused damage to timber surface referred to as "fibrillated surface" which gives the look of the timber elements a "fuzzy" character.

The in situ surveys of damaged timber construction elements proved that the fibrillated timber layer manifests a considerable loss of cohesion and deterioration of mechanical properties. Timber members were identified as belonging to norway spruce (*Picea abies* (L.) Karst.), silver fir (*Abies alba* Mill.) and scots pine (*Pinus sylvestris*). The objective was to determine to what depth chemical corrosion reaches and how much mechanical properties are affected. Mechanical properties in timber at particular levels of damage were established by special tests of small tensile samples. The samples were taken from the truss construction of a former brewery malthouse in Děčín (North Bohemia – CR) (Fig. 4). The surface of the timber investigated manifested an advanced level of fibrillation (Fig. 5).

The tensile strength parallel to the grain was tested using small triangular samples (5 × 5 × 7.5 mm) 200 mm long. The specially made small samples allowed for a more accurate establishment of property investigated at various depths under the surface of damaged timber. The samples were made from the superficial layer of the timber (0–5 mm – damaged layer) and the inner part of the timber (25 mm deep – undamaged layer, reference samples). The considerable deterioration of mechanical properties of timber in the damaged surface layer was manifested by a 50% decrease in strength compared to the values ascertained in undamaged timber (Table 1). The surface was damaged to a depth of 5 mm, which was confirmed using small tensile samples [11].

2.4. Summary

The testing of small tensile samples is a direct and partially destructive method which can be used for the measurement of modulus of elasticity and tensile strength parallel to the grain. The method is not compromised by uncertain correlations between the measured and the estimated parameters. The tensile properties of small clean wood samples are measured directly but their information capacity is reduced by the high variability of results dependent on the proportion of earlywood versus latewood, The method only gives information about timber in close vicinity to the surface

Fig. 6. Extraction of mesospecimens using a jig saw.

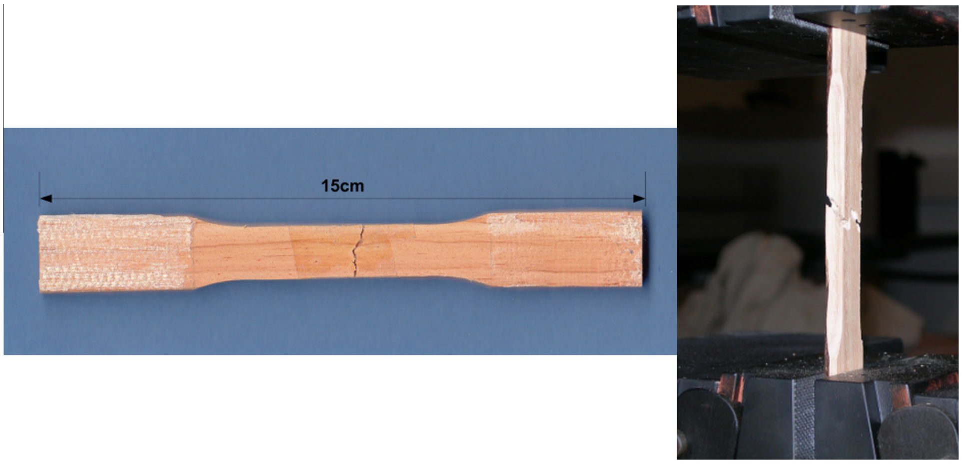


Fig. 7. Mesospecimen and testing apparatus.

of the element, similar to other methods described as tension over mesospecimens or the hardness test.

2.5. Recommendations

It is recommended to choose a sufficiently large part of the timber surface without defects – typically, a band of 20 mm × 300 mm is needed for the method application. Sampling demands that the guides are fixed either directly on the surface or on an auxiliary construction so that the sampled band area merges with the plane of the guides. The band axis needs to be in the same direction as the axis of the guides and the direction of fibers. It is recommended to determine the fiber direction using light scratching the surface between the annual rings. If, for the reasons of the element geometry, the sampling orientation cannot be maintained, it is necessary to correct the strength values measured based on table dependences e.g. [12]. The samples in the test need to be loaded coaxially so that their bending and thus effect on measured quantities are prevented. Moisture content should be measured or controlled during sampling and laboratory testing as the values of mechanical properties decrease with increasing moisture content. Moisture content of 12% is recommended for the tests. Accurate measuring of sample dimensions is a prerequisite for the test interpretation and establishment of mech. properties.

3. Tensile Young's modulus of mesospecimens

3.1. Testing methodology

Timber modulus of elasticity parallel to grain shows a moderate dependence on the type of loading and it can be considered independent of the load involved for clear wood specimens. Therefore tension modulus of elasticity can be used as estimator of the bending and compression modulus as already stated in the previous section.

The sampling included collection of four wooden samples from the arris at four locations along the length of the timber member. Each sample consisted of a triangular prism with cross sectional dimensions 15 mm × 15 mm × 25 mm and length 150 mm. The location where to extract the wooden samples is a decision to be made by the expert taking into the consideration the type of load acting on the timber member. The extraction of the wooden samples can be done using an electric jig saw, Fig. 6.

At the lab the wood samples are prepared to obtain the final dumb-shell-shaped test specimen (Fig. 7). The small cross-section of the specimens at the testing zone (uniform cross-section – 10×5 mm^2) allows the test to be carried out at the scale of a single growth ring. For this reason the specimens are called mesospecimens.

The mean and standard variation of testing of the four specimens is used as estimation of the tension modulus of elasticity parallel to the grain. The comparison of the results from mesospecimens and standard specimens [13] showed that this method is suitable to assess the tensile modulus of elasticity of clear wood zones. However this method is less reliable for the estimation of the tension strength.

3.2. Limitations

The results obtained represent only the tension properties of the external layer of the timber members at a particular location in the beam. The method requires that a minimum of four mesospecimens should be tested to account for the strong effect of the spatial variation of properties (lengthwise and across the cross-section). Reliability of the results can be enhanced by taking more samples and by applying other semi-destructive methods (e.g. drilling resistance, X-ray, stress waves).

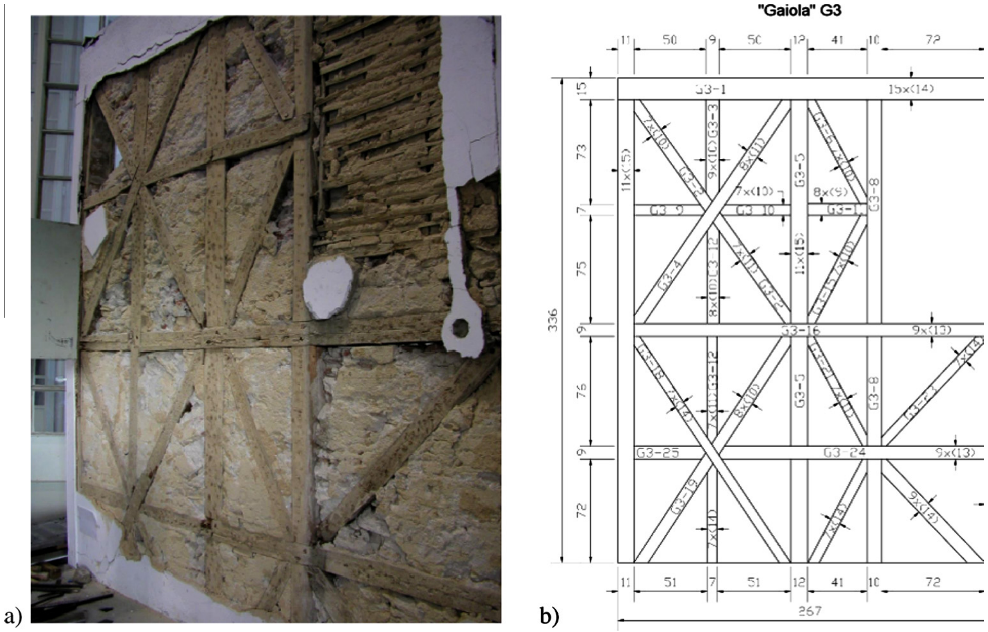


Fig. 8. "Gaiola" after testing (a); dimensional (mm) survey of the timber members.

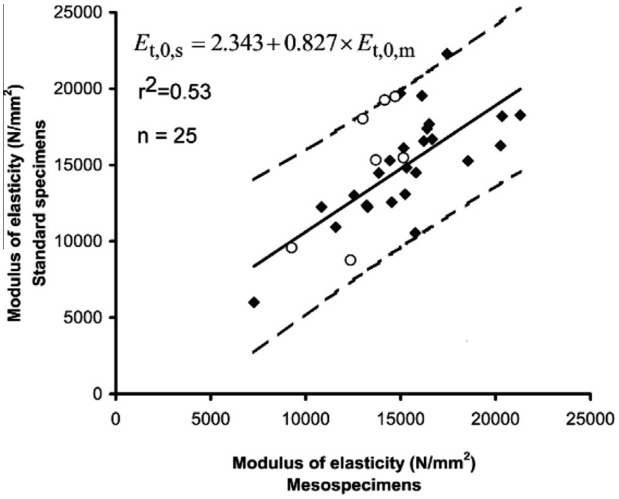


Fig. 9. Regression model and prediction interval (95% confidence) corresponding to the correlation between meso and standard specimens (rhombus shapes); circles correspond to new data (extract from "Gaiola").

The scarce number of growth rings under testing can affect the representativeness of the result provided by the mesospecimens. Therefore the results are sensible to the variation between earlywood and latewood properties. Furthermore this method only provides information about the tension properties of clear wood zones. Therefore it should not be used as a standalone method but instead used in combination with information obtained from other non or semi-destructive test methods capable to assess the strength-reduction effect of defects (in special knots and slope of the grain) and the state of conservation of the timber members.

3.3. Application

The development and validation of this method was based on the correlation between the meso and standard test methods used for the characterization of clear wood species (the Brazilian standard was followed given the similar geometry of the test samples) [13]. The resulting average value obtained from meso and standard specimens are very similar showing a meso/standard ratio of 0.98 (results obtained for 25 maritime pine beams – *Pinus pinaster*, Ait.) or 1.05 (results obtained for 25 chestnut beams – *Castanea sativa*, Mill.). As mentioned before some precautions should be taken as

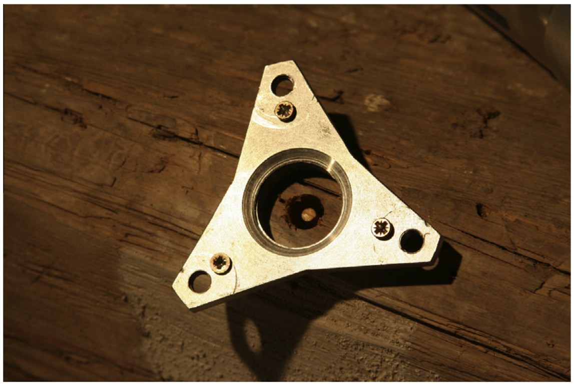


Fig. 10. Taking a cylindrical sample.

Fig. 11. Equipment for sampling of radial cores.

regards tension strength since the average ratio meso/standard obtained is 1.38 (maritime pine) or 1.22 (Chestnut).

This method was used for assessing the stiffness values of timber elements on an internal wall removed from a Pombaline building (Fig. 8). Pombaline buildings designate a type of anti-seismic construction used for the reconstruction of downtown area of Lisbon after the large earthquake of 1755.

The racking strength of the wall was determined (tested under combined constant vertical loading and cycling horizontal loading) and a FEM model was developed [14]. Afterwards four mesospecimens from each timber member were collected and prepared. One standard specimen was collected from those members where it was possible to identify a clear wood volume without damage.

The result showed the relationship between the standard and mesospecimen modulus of elasticity of 1.14. The possibility of using the same model developed during the calibration of the method was verified by plotting the results against the regression model obtained for *P. pinaster* Ait. in [13], Fig. 9. The results showed that the values are within the boundaries of the prediction intervals defined for the regression model (Fig. 9), and therefore the model could be used for prediction of the modulus of elasticity of the timber members.

The experimental and FEM results indicate that as expected the joint's stiffness controls the deformation of the wall [14]. Therefore for analyzing timber structures, specific studies on the behavior of traditional joints should be carried out. Also one of the problems regarding Pombaline buildings is the large amount of changes made to the original structures over time.

3.4. Summary

Tensile test of mesospecimens is a method developed for the assessment of the tension parallel to the grain based on properties of clear wood zones of timber members in situ [13]. It provides direct information on the stiffness of clear wood zones of timber members and it was envisaged so that a minimum volume of wood is extracted and therefore at least four specimens could be tested per timber member. The loss of material from the beam corresponds to the presence of wane within the limits generally acceptable by visual strength grading standards. The method was also designed so that the extraction process could be simple and easy to perform in situ.

As for the tensile strength of small samples (Section 2) mesospecimens can only provide information about the properties of the external surface layer of timber members. Although no correlation was determined between small samples (Section 2) and mesospecimens it can be envisaged that they will provide similar results when evaluating the same clear wood area of a timber member. This conclusion is supported in the comparison between the volume of material under tensile test from both methods, 8–12 mm^2 and 50 mm^2 for small and mesospecimens, respectively. Both tests tested the material at the meso scale (growth ring).

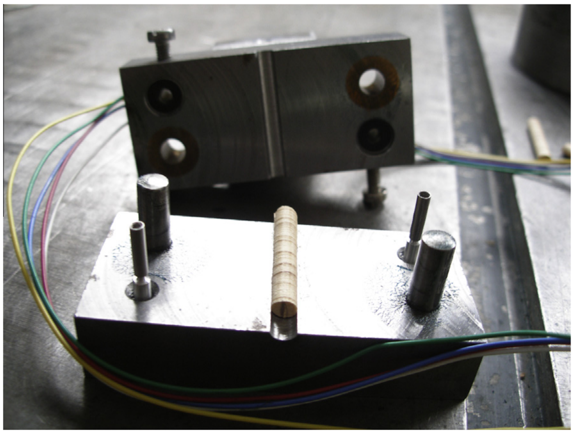


Fig. 12. A detail of the loading device.

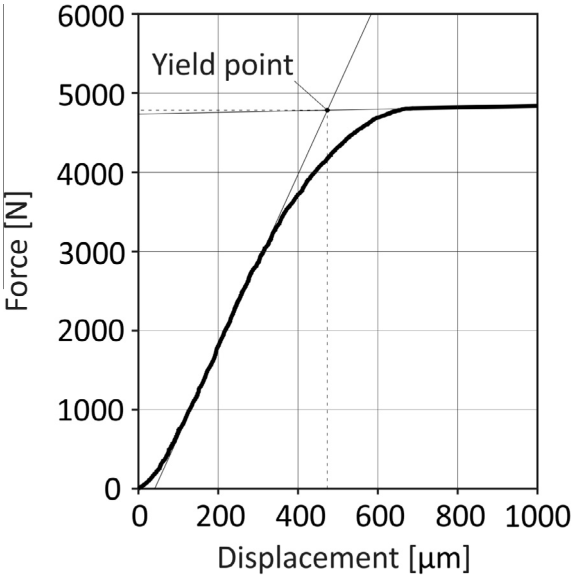


Fig. 13. An example of the stress–strain diagram for the compression test of a radial core.

3.5. Recommendations

A minimum of four mesospecimens per timber member should be collected from each timber member. The specimens should be prepared such that the longitudinal axis of the mesospecimens coincides with that of the timber member. In this way the effect of slope of the grain is taken into account. The mesospecimens should be conditioned for a moisture content of 12% before testing.

4. Compression strength of cores

4.1. Testing methodology

Testing radial cores is a semi-destructive method. Samples are of a cylindrical shape (Fig. 10) and they are used to establish the strength and modulus of elasticity in compression parallel to the grain using a special loading device [9]. The holes that remain after sampling are smaller than most knots that appear in timber elements and they do not reduce the element strength considerably thus meeting the recommendations and charters in the field of built heritage conservation regarding low invasiveness [7]. The sampling holes can be plugged to prevent moisture penetration, insect attacks, probability of decay or if aesthetic qualities are to be preserved [15]. Radial cores are 4.8 mm in diameter and the holes in the element are 10 mm in diameter. The length of the cores should be at least 20 mm to ensure reliability of results and eliminate enough result variability based on early- and latewood alterations.

Radial cores are taken using an electric drill with a special bit (Fig. 11), which was developed in Institute of Theoretical and Applied Mechanics, Czech Academy of Sciences (ITAM/CAS). Occasionally, soap or wax is applied to facilitate drilling. The drilling speed must be constant and the drilling is usually performed in steps to prevent damage to samples. The bit tip must

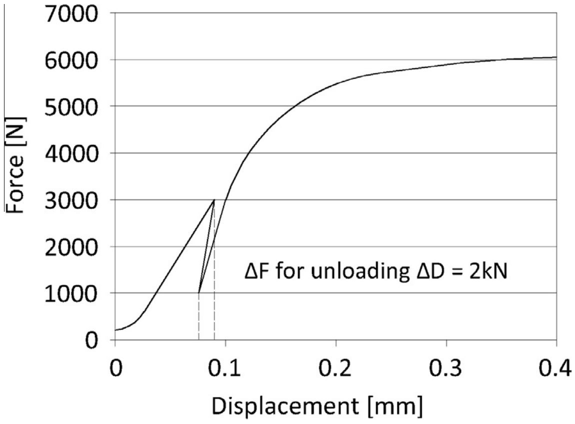


Fig. 14. Stress–strain diagram force – compression with partial release [13].

be sharp and clean. Blunt and dirty bits cause damage to samples. The samples are transported to the laboratory in containers that prevent their damage and change in moisture content. The containers are marked with a number, place and date of sampling and other important information [10].

The samples should be extracted from healthy and undamaged material in the radial direction because the tree-ring orientation is an important basis for correct testing. The shear forces that can be very high during drilling make the sampling conditions unfavorable. Therefore, the drill construction eliminates them. Due to the threat of drill sideways motion, the drill is fitted in a special device ensuring fixation and constant progress of the bit into the material. Radial cores can be used for examining other properties of wood such as density, moisture content, modulus of elasticity and compression strength parallel to the grain. It can also be used for the determination of the tree species, dendrochronological dating, microscopic analysis of decay, and visual evaluation of the element condition and the penetration of protective agents [16].

The actual testing of radial cores uses testing grips with grooves that facilitate loading in the direction perpendicular to the core axis, i.e. parallel to the grain (Fig. 12). Two linear-variable displacement transducers (LVDT) are used for monitoring the distance between the grips and thus the radial core deformation. A correct insertion of the radial core in the testing apparatus is critical for the correct determination of the compression strength and the modulus of elasticity. Wood has the highest strength in the grain direction, and uncensored radial cores in the grips lead to higher variability of results [17]. The compression force and the core deformation are recorded in a stress–strain diagram, see Fig. 8. The compression strength is calculated as follows:

$$f_c = \frac{F_{\max}}{l \cdot d_c} \quad [\text{MPa}] \tag{2}$$

where f_c – compression strength [MPa], $F_{\max}$ – load [N], load $F_{\max}$ is taken from the diagram, see Fig. 13, l – radial core length [mm], d_c – radial core diameter [mm].

Ref. [17] found the correlation between the strength of radial cores and the strength of standard specimens in the longitudinal direction. [16] established the coefficients of determination in the interval $R^2 = 0.77–0.96$ for the same relationship, based on the wood species. [15] found a strong dependence between moduli of elasticity in compression parallel to the grain for radial cores and [18] clear wood samples (American Technical Standard), coefficient of determination $R^2 = 0.89$. The variability of measuring is comparable for both methods [15]. One of the problems when establishing the regression between the properties of radial cores and standard specimens is the destructive character of both methods due to which both of the methods cannot be used for absolutely the same samples.

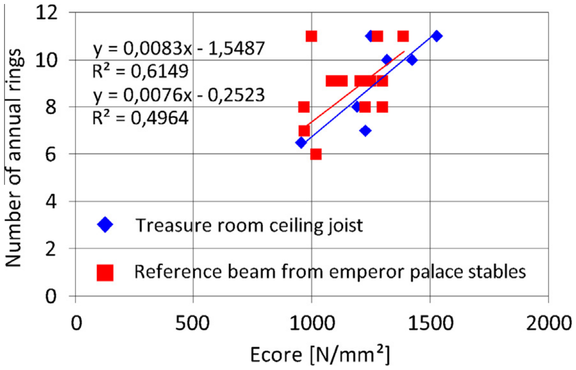


Fig. 15. Correlation of pressure deformation characteristics of the radial cores with the number of annual rings.

4.2. Limitations

Due to the dimensions of the radial cores, this method is of local character. Therefore, it may not provide relevant information about the condition of the integrated timber because of wood variability. This inefficiency can be eliminated and the reliability increased with a higher number of samples taken from one element. However, this step would increase the damage done to the element, the time consumed, and the expenses of field measuring and the strength of the element would decrease [15]. The testing sample is extracted using a special bit which is fixed in an electric or manual drill (Fig. 11). The bit outer diameter is 9.5 mm. Speed is controlled during drilling so that the samples are not damaged. For the same reason, the bit tip needs to be kept sharp and clean. Blunt or dirty bits can cause that the samples look damaged or decayed, or they can be pushed outside the bit, which creates distortion of results. The samples should be extracted from healthy and undamaged material in the radial direction because the tree-ring orientation is vital for the correct test. The shear forces that can be very high during drilling make the sampling conditions unfavorable. Therefore, the bit inner diameter decreases towards the tip. To eliminate a possible sideways motion the bit is fitted in a special device which ensures fixation and constant speed towards the material.

Radial cores can be used to establish physical, mechanical and strength properties of timber. When investigating moduli of elasticity, it is necessary to release the load partially from the radial core during testing (Fig. 14) and then measure the elastic response of the core to the change of external loading only; otherwise, considerable inaccuracy occurs [19] as the total sample deformation is affected by the plastic deformation in the places of contact with the grips. Radial cores can also be used to determine density. This is especially important for valuable timber elements, in which every piece of material matters. The variability of the data gained is comparable with standard tests. However, radial cores need to be taken from undamaged places.

4.3. Application

Radial cores have been successfully used for non-destructive surveys of timber constructions e.g. with the aim to find out mechanical properties of a timber construction of storage halls in the trade fair facilities in Brno (South Moravia – CR) or the quality of the ceiling timber in the St. Mary's Tower of the Karlstejn castle (Central Bohemia – CR). In the case of the St. Mary's Tower, we had a sample of an authentic beam from a damaged part of the building (emperor palace stables). We used this piece for calibration tests in compression parallel to the grain in compliance with [18]. We tested short columns cut from the beam with exactly oriented fibers. Further, radial cores were sampled so that each standard sample by ASTM was matched with two cores taken from each end of the specimen. In total, 38 radial cores were available. Typical deformation properties (modulus of elasticity in compression parallel to the grain) were investigated using both the radial core samples and the standard samples. The values correlated very well. The mean values for the modulus of elasticity and compression strength ranged around 7600 N/mm^2 and 42 N/mm^2, respectively. The characteristic values with 5% quantile followed, reduced based on the appearance of defects in the element. For the reduction, visual assessment was used [20].

Further, non-standard tests were conducted using 12 radial cores from the joist of the treasure room ceiling. The deformation characteristics measured correlate with the tests of cores from the reference beam from the emperor palace stables. The comparison shows that the mechanical properties of the treasure room ceiling timber elements were of the same quality as the reference beam whose strength and modulus were established by ASTM standard tests (Fig. 15). The values of mechanical properties showed a very high quality of the historic timber. These values could be used to determine design characteristics for the purpose of construction safety assessment in a common way [20].

4.4. Summary

Radial cores are to be used for a direct establishment of physical (specific density), morphological (tree-ring width) and mechanical properties (compression strength parallel to the grain and modulus of elasticity) with a relatively high accuracy in defectless timber. The cores can also be used for microscopy, dendrochronology, visual assessment, and measuring of protective agent penetration.

4.5. Recommendations

The cores need to be taken with a special hollow bit in the radial direction, i.e. Normally oriented to annual rings so that the test of mechanical properties can be performed parallel to the grain. An area with a diameter of about 70 mm is needed for the sampling as the drill fittings need to be fixed. The fittings ensure the bit movement in the radial direction without deviations and allow for a gradual drilling to the demanded depth with constant speed. After the demanded core depth is achieved (usually 40 mm), the bit is taken out and a thin-walled tube is inserted. The tube is used to take the core out of the timber. The core is then pushed out of the tube. Broken or damaged cores are excluded from the test. Moreover, the core needs to be placed into the testing grips with high accuracy. Moisture content of 12% is recommended for the tests. Accurate measuring of sample dimensions is a prerequisite for the test interpretation and establishment of mechanical properties.

Fig. 16. A detail of a drawbar with a push-apart wedge and rounded grips.

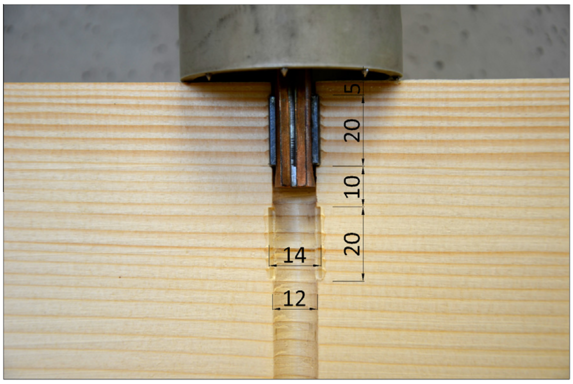


Fig. 17. A view of the device.

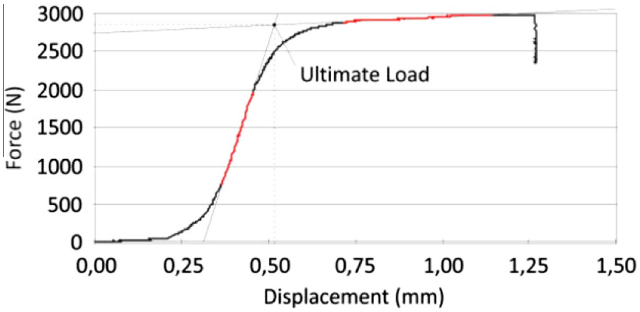


Fig. 18. Example of the device output: record of the force of grip pushing apart related to the measured distance of movement of the grips.

5. Compression strength in a pre-drilled hole

5.1. Testing methodology

The range of the existing methods and devices lacked a solution enabling the measurement of mechanical properties of wood using gently destructive investigation and eliminating the time-consuming stage of preparation of samples for testing at the lab. Execution and interpretation of tests in situ provides real-time data which improves the efficiency of the survey work. With in situ testing, it is possible to make decisions onsite and to choose whether to make additional tests or not based on more information (using the same method or a combination tools). Thus, this method contributes to more reliable prediction of mechanical properties and strength grades and therefore a reliable structural analysis [17]. The method consists of measuring the compression behavior of clear wood zones of timber members as they are loaded by a miniature loading jack inserted into a pre-drilled hole (Fig. 17). During the application, the dependence of deformation on the voltage is measured while symmetrically arranged grips (“stones”) are pushed apart in a pre-drilled radial hole with a diameter of 12 mm [21]. The semi-destructive procedure of making a hole into the tested material allows the investigator to assess other aspects of the material condition (e.g. based on the core, sawdust, videoscopy, etc.).

The device can be used both in the laboratory and in the field to assess the condition and the quality of timber. The advantage of the device is the possible gradual recording of the force and shift of grips (loading jack) at different depths corresponding to the required dimensions of commonly investigated constructions. The device is laid on the tested unit (usually a constructional element of a rectangular profile) by means of a cylindrical shell, which allows for measuring in four positions of the pre-drilled hole. The shell arresting is assisted by two grooved screws, for testing positions (core depths) 5–25, 35–55, 65–85, and 95–115 mm. When the measuring part of the device is inserted in the drilled hole and the device is laid on the tested element, the rounded grips are pushed apart by the drawbar with a push-apart wedge (Fig. 16) into the walls of the hole. The maximum depth of possible loading on both sides is 1.5 mm. The rounded grips are 5 mm wide and 20 mm long. The grips also include flexible arms whose movement during pushing is provided by a push-apart bronze wedge fitted to the lower end of the drawbar by means of a pin and screw. The apex angle of the wedge is 15°. This angle is not self-locking and to release the grips it is sufficient to release the push-apart force [22].

The force of the drawbar when pulling out is continually scanned and recorded. It is calibrated to the real force of the loading jack and simultaneously related to the measured distance of movement of the grips (Fig. 18). The signals are wirelessly transmitted to a portable computer, where they are processed.

The article [21] introduced the construction and usage of this new device for in situ assessment of integrated timber. The application of the new device was verified. It was found that the device is sufficiently sensitive to the natural differences between individual elements of healthy timber. Strong correlations were mainly found between the $CS_{C(L)}$ strength in compression parallel to the grain and $S_{C(L)}$ strength of standard samples assessed in compliance with [21] (correlation coefficient 0.92). The relations were described by simple linear regression models. The measured compression strength parallel to the grain correlates with other investigated timber parameters, e.g. density (correlation coefficient 0.87). Another parameter for the assessment of mechanical properties using the new device was $MOD_{(L)}$ modulus of deformability, which correlates well with $MOE_{(L)}$ modulus of elasticity parallel to the grain (correlation coefficient 0.87). The construction of the device is lightweight and due to its independence from the electrical grid, it is easy to use in the field. In contrast to other methods, the new device enables a highly accurate establishment of mechanical properties in the entire depth profile of the assessed element.

Fig. 19. Truss of the St. Mary's Church in Vranov nad Dyjí.

Fig. 20. Longitudinal sections four samples of tie beam [26].

5.2. Limitations

The prerequisites of an appropriate use of the method are drilling a hole through the wood fibers purely in the radial direction, where there is a regular alternation of earlywood and latewood within annual rings, and the orientation of the measuring probe to measure the strength parallel to the grain. In structural elements it is generally parallel to the axis of the element. Measuring is affected by a higher proportion of earlywood or latewood within a tree ring in the tangential direction, which leads to distorted results. The hole needed for the test is created by a bit which is fixed in an accumulator drill. To prevent sideways motion of the bit, the drill is fitted to a special stand which fixes it to the element. The outer diameter of the bit is 12 mm. Speed is controlled during drilling so that the hole is not damaged. For the same reason, the bit must be maintained sharp and clean. Blunt or dirty bits can cause fibers being torn out of the hole walls, which distorts the results. The hole should be made to undamaged places of the element without visible defects and damage.

An essential feature of the in situ testing is the fact that the measuring of a loaded element is conducted with unknown internal forces present. It was assessed and approved by measuring the deformation around the drilled hole using image digital correlations that show that the state of tension recedes after drilling into a distance of about 2 mm from the hole edge and the measuring is thus not affected by the inner tension of the constructional element unless the element was damaged by exceeding the elasticity limit. The above mentioned assertion has been verified by tests of a bended timber console [25].

5.3. Application

The method for the establishment of strength in a pre-drilled hole has been successfully used for the investigation of mechanical properties of the timber truss of the St. Mary's Church in Vranov nad Dyjí (Fig. 19) from the 17th century (South Moravia – CR) or when investigating the quality of a larch ceiling from the 14th century in Spišské podhradí (UNESCO site – SK).

In the case of the Vranov nad Dyjí truss, four samples of tie beam ends were available. They were taken away because the timber scarf joints were to be used instead of the damaged ends (Fig. 20). The aim was to verify the application of the device using the wood of Silver Fir (*A. alba*, Mill.) in the common variability of properties of timber integrated in a historic building. The measurement by the new device was conducted in 135 positions. Decayed beam ends were also measured but due to the low values gained, the results were not taken into account [26].

Mechanical properties were determined from the record of measured data in the form of a stress–strain diagram showing the force of drawbar while pulling out the drill, which was calibrated to the real force of grip pushing apart and simultaneously related to the measured distance of grip movement. Measured strength CS_C was determined from the ratio of the ultimate load and the area of the grips. The modulus of elasticity cannot be calculated from the stress–strain diagram directly; however, the modulus of deformability was determined based on the force slope and deformation. The new device was verified by experiments based on the comparison of values measured as the grips were pushed apart in a drilled hole and the results of standard sample testing by destructive tests in compliance with [23,24] using a universal testing device. Two standard samples with dimensions 20 × 20 × 30 mm, complying to [23,24] were cut from places adjacent to the positions measured by the new device. Compression strength parallel to the grain established based on the standard samples was correlated with the results of the new device [26].

Strong correlations were mainly found for $CS_{C(L)}$ measured strength in compression parallel to the grain and $S_{C(L)}$ strength of standard samples (correlation coefficient 0.75). The relationships were described by practice oriented linear regression models. Similar dependences were found when the pin penetration device is used [6]. The initial tests conducted using timber from the historic truss construction showed that the new method is sufficiently sensitive to natural changes in properties (distribution along the element width). It should be noted that the natural material variability was increased by the presence of defects (knots and cracks).

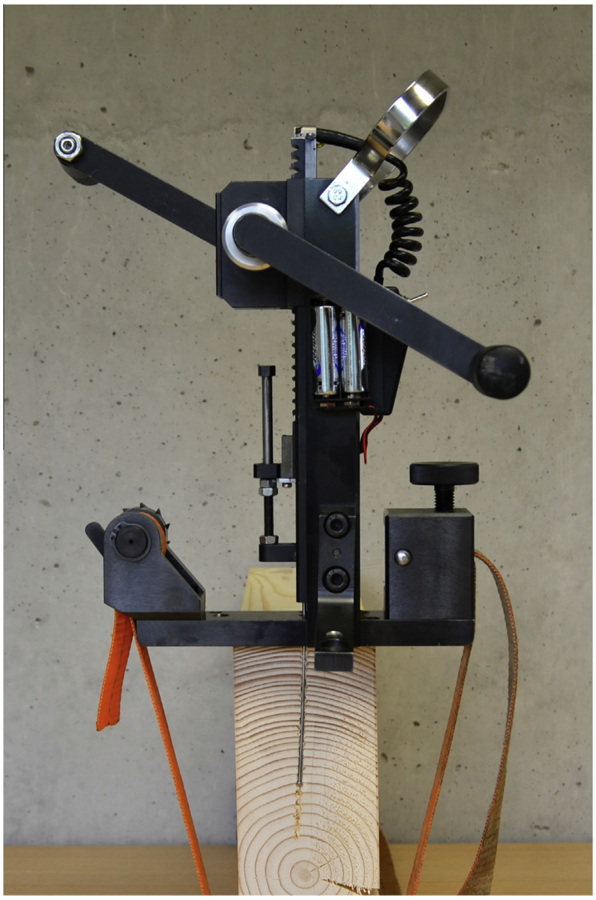


Fig. 21. A view of the device for in situ.

Fig. 22. A detail of pin penetration through the device base during pin pushing.

5.4. Summary

The advantages of this method include the high accuracy of the establishment of mechanical properties (measured strength and modulus of deformability in compression parallel to the grain) of timber tested and assessed in the field. In contrast to other methods, the new device is able to establish mechanical properties in the entire depth profile of the assessed element. The measuring is accurate if the drilling is oriented perpendicularly to the grain in which direction early- and latewood alternate regularly within annual rings and if the grips are pushed apart parallel to the grain or parallel to the element axis in the case of constructional elements. The effect of a larger proportion of earlywood or latewood in the tangential direction leads to distortion of results. The results of measuring depend on the quality of the drilled hole production, i.e. it is necessary to check the bit constantly and replace blunt bits immediately.

5.5. Recommendations

To guarantee the planeness of the drilled hole and to eliminate sideways motion of the bit, the drill needs to be fixed to the assessed element by means of a special stand during drilling. The stand can be fixed to the element directly or via an auxiliary construction. The fixing demands an area of 150 × 150 mm. To ensure a good quality of drilling, it is recommended to control the drilling speed, especially as the bit progress into the hole. The hole should be drilled in an undamaged part of the element without natural defects and visible damage. A higher number of holes improperly placed can affect the mechanical resistance of the element assessed. Like other in situ methods used for the diagnostics of integrated timber, this method for the measurement of strength and modulus of deformability manifests a considerable dependence on the moisture content in the investigated material. Therefore, the measuring of moisture content in the tested place is an essential part of the test.

6. Mechanical resistance to pin pushing

6.1. Testing methodology

A device for in situ establishment of mechanical resistance to gradual pin pushing was developed in cooperation with the Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences and the Department of Wood Science, Mendel University in Brno. The device measures the demanded values to the depth corresponding to typical dimensions of timber constructional elements and is applicable for an indirect establishment of density and mechanical properties of wood. Similar penetration test is based on repeated pin hammering into the wood by means of a hammer with constant energy [5].

The device body can be fixed to the tested element in various ways, most often with a fabric strap (Fig. 21) or a roller chain. The device body can also be fixed to the tested element by mounting screws. After the device has been fixed to the object, a pin is gradually pushed into the timber perpendicularly to the device base (Fig. 22) by a toothed rack and pinion gear driven by two opposite manual cranks for both hands. The force of pin pushing is continuously recorded in relation to the distance measured [27,28]. The measuring application processes the data, shows them in real time and saves them. The progress of force measured in real time is shown either in dependence on time *x-t* or in *x-y* mode together with pin displacement. During the measurement, basic characteristics are calculated by a PC. These are work [N mm] as the area under the force curve related to the displacement, penetration length [mm], time of pin displacement [s] and the maximum and minimum force [N]. The mean force [N] necessary for pin pushing is calculated by dividing the area under the curve by the penetration depth. This parameter is of key importance for the assessment of the timber mechanical resistance [27,28].

The continuous record of the force related to pin displacement is able to indicate a change in properties within the entire depth of pin penetration caused by either a natural distribution of properties or biodegradation. The curve of forces in the case of undamaged spruce (Fig. 23) corresponds to earlywood and latewood alternations within annual rings (latewood with a higher mechanical resistance and early wood with a lower mechanical resistance). The curve also describes the different tree-ring widths (increments) in the element cross-section. The general progress reflects the equal distribution of mechanical resistance in the cross-section, i.e. a balanced quality of sound spruce timber.

When measuring the resistance of pine wood, there is again a visible difference between latewood and earlywood as well as the tree-ring widths (Fig. 24). The record with increasing forces reveals that there is heartwood typical of pine wood with a higher density and mechanical resistance. The absolute values of forces correspond to the mechanical resistance to pin pushing in sound pine wood. Fig. 25 shows a record of measuring a spruce element containing biodegradation. The relative decrease in the zone with decay compared to sound wood and the absolute force values indicate a decrease in mechanical resistance.

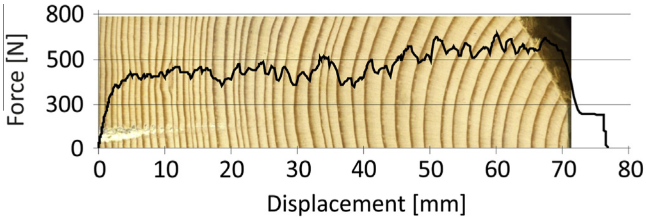


Fig. 23. Record of the force related to pin displacement – spruce wood.

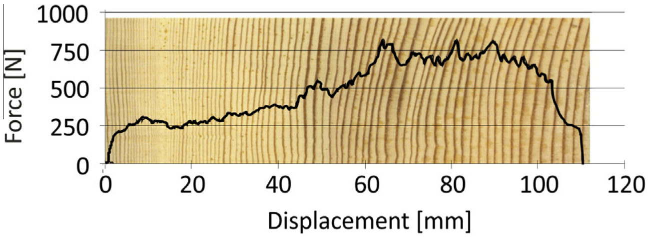


Fig. 24. Record of the force related to pin displacement – pine wood.

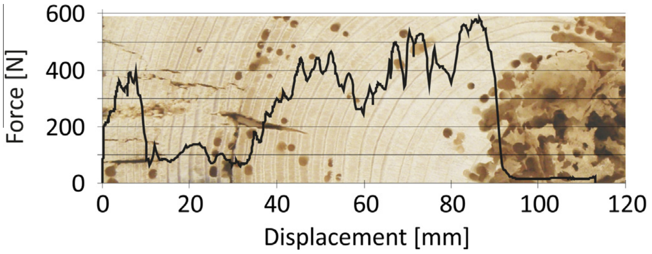


Fig. 25. Record of the force progress and displacement of pin pushing into spruce wood with decay and feeding of wood-damaging insects [29].

Fig. 26. Investigation of a tie beam condition using pin pushing.

Fig. 27. A detail of damage to a tie beam, which was left in the original position.

To sum up, the device is applicable for measurement of a wide range of properties of sound quality as well as damaged wood. The test results manifest very good correlations of the mean force needed for pin pushing with wood density and strength determined using standard samples in compression perpendicular and parallel to the grain [30,31]. The measured parameter can be changed by a simple replacement of the indentation pin with a hook for withdrawal of screws or other fixings, as for example presented in [32].

6.2. Limitations

The device was designed and tested for the assessment of wood integrated in buildings, both of sound quality or with various levels of degradation. The device records a relatively wide range of timber mechanical resistance to pin pushing caused by natural properties of different tree species as well as different levels of degradation. The resistance is affected by the species, wood quality and density but also moisture content [29]. These parameters need to be taken into account when interpreting the results. Potential wood defects, such as cracks, knots, foreign objects, etc. considerably distort the results. It is advisable to avoid measuring in places with wood defects, or interpret results of such measuring very cautiously. It is necessary to push the pin into wood in the direction perpendicular to fibers – only in the radial direction – where earlywood and latewood alternate regularly.

6.3. Application

Visual inspection of the flat roof truss construction of the Čechy pod Kosířem Castle Orangery (North Moravia – CR) conducted in 2011 proved that the truss and ceiling timber is locally damaged by wood rot and insects. Damaged places were found at the ends of tie (ceiling) beams, where rainwater had leaked and had provided favorable conditions for brown rot. The resulting rot changed physical properties of the timber (color, decrease in density, increase in absorption, etc.). Wood mass was considerably disintegrated at some places. The wood-decaying insects identified as the cause of the general damage of constructional elements were Cerambycidae or Anobiidae. The attacked tie beam had to be replaced or fitted with scarf joints. The renovation needed to be approached with utmost caution and maintain the largest possible proportion of historic material. The construction of the Orangery truss was divided into 25 cross sections, each containing a tie (ceiling) beam and a rafter. The construction renovation of the truss was designed based on visual inspection and mainly results of mechanical resistance measuring by the diagnostic device with a pin 2.5 mm in diameter (Fig. 26). A third of the total volume of the elements was deemed for replacement. The accurate establishment of damage helped save a large part of the material, which despite the surface damage (Fig. 27) met the necessary mechanical properties to the same or higher extent than new timber.

Fig. 28 shows the record of measuring of a tie beam with surface rot and damage by wood-damaging insect feeding. The measuring was conducted using the device with pin pushing method. The device was fixed to the element by a fabric strap and the force needed for pin pushing was developed continuously by two cranks (Fig. 28). The distance and force were recorded during pushing. The relative decrease in the zone with rot and feeding compared to sound wood and the absolute force values indicate a decrease in mechanical resistance caused by degradation to a depth of 15 mm only.

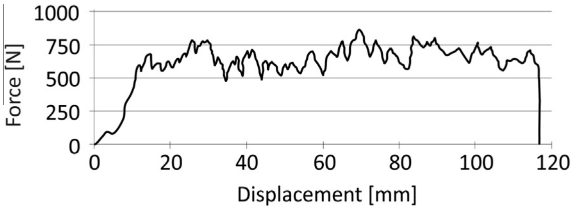


Fig. 28. The record of measuring tie beam 8 northern end, where only 15 mm layer of surface was damaged.

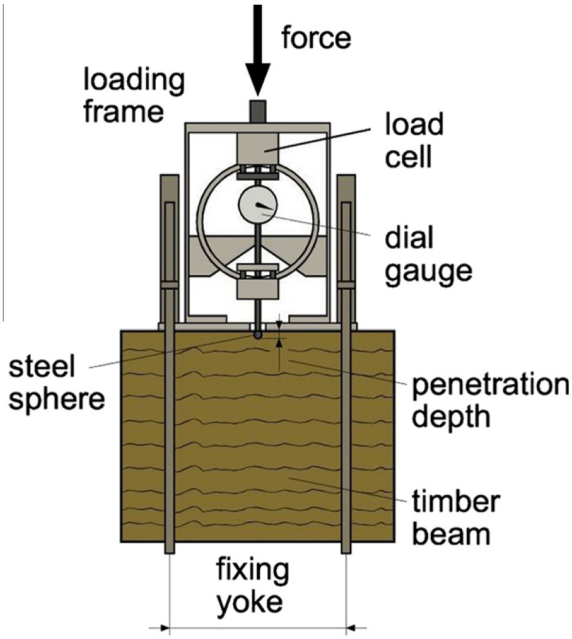


Fig. 29. Hardness test device [29].

6.4. Summary

The method of measuring the wood mechanical resistance to pin pushing can be used to estimate parameters of wood density and strength, up to a depth of 110 mm. By contrast to the commonly used Pilodyn, this method provides data about a larger cross-section part of the tested element and allows the researcher to identify internal defects hidden deep below the timber surface. The slow progress of pushing enables the researcher to quantify damage in any depth. The size of the resistance recorded is affected by the wood species, wood quality and density, as well as moisture content. These parameters need to be considered for a correct interpretation of results. Potential wood defects, such as knots, cracks, foreign objects, etc. distort the results considerably.

6.5. Recommendations

The test demands a free area of 150 × 150 mm so that the device can be fixed. It is recommended to avoid measuring in places with defects as the interpretation of results is then difficult. Pin pushing is only accurate if the device is fixed perpendicular to the grain and if the pin penetrates the timber in the radial direction. The acceptable deviation is about up to 10° from purely radial direction. When the pin is pushed in the tangential direction, the results may be distorted as the pin then often penetrates the weaker earlywood only and does not enter denser latewood increments in heterogeneous wood types. The measuring of moisture content in the tested place is again an important part of the test.

7. Young's modulus derived by hardness test

7.1. Testing methodology

Hardness is generally defined as resistance to indentation. Wood hardness involves compression strength, shear strength and fracture toughness. It is positively correlated to density, and, as a consequence, to the material strength properties, and is in inverse proportional to the moisture content.

The hardness test proposed by Piazza and Turrini [29] is a modified Janka hardness test. As known, Janka modified the Brinell-hardness test for wood, based on the force required by static loading to embed completely a steel hemisphere into a wood surface. The Janka hardness test became a standardized procedure for *clear wood* [33]. Although *hardness* originally expressed by Janka was a load divided by the projected area of contact, ASTM D143 [34] specified hardness as the load (H) at a certain penetration. The modified Janka test proposed by Piazza and Turrini herein can be easily applied on site for existing timber elements by using a variable load to produce a given depth of impression on the lateral surface of wood, orthogonal to the grain direction. The Piazza and Turrini hardness test is a SDT for the mechanical characterization of timber structural elements, using appropriate correlations [35].

The hardness test proposed measures the force R required to embed a 5–10 mm diameter steel hemispherical bit. The experimental test equipment is shown in Fig. 29. In order to estimate the global behavior of a structural element the value of R must be obtained by averaging the test results made on the longitudinal faces of the element. The value of R was obtained by averaging the results of two tests for two opposite longitudinal faces, in particular at 1/3 and 2/3 of the span. Each test consists in five measurements taken in a limited portion of the element. The result is obtained by averaging three median values among the five measures. The method, however, is specifically conceived for assessing structural timber on site, specifically and primarily the modulus of elasticity and a correction factor δ which is introduced in order to take into account the presence of defects:

Table 2
Values of δ as a function of the size of defects.

Characteristics	δ		
	0.5	0.68	0.8
Single knots	⩽1/5 ⩽50 mm	⩽1/3 ⩽70 mm	⩽1/2
Group of knots	⩽2/5	⩽2/3	⩽3/4
Slope of grain	⩽1/14	⩽1/8	⩽1/5
Checks	–	–	Limited

Fig. 30. The queen-post truss of "Teatro Sociale" (Trento, Italy) [35].

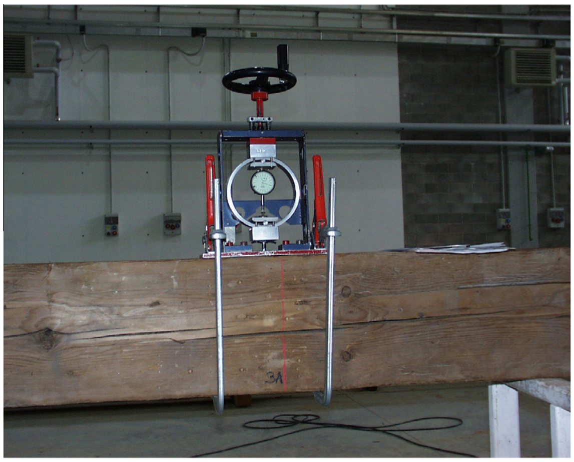


Fig. 31. The hardness test device applied on the lower chord of the truss.

Fig. 32. The queen-post trusses of "Teatro Zandonai" (Rovereto, Italy) [38].

Fig. 33. Val Cadino timber bridge [39].

$$E_{0,\mathrm{mean}} = \delta \cdot A \cdot R^{0.5} \quad [\mathrm{MPa}] \tag{3}$$

where $E_{0,\mathrm{mean}}$ – Young's modulus in longitudinal direction [MPa], δ – correction factor taking into account the anatomic defects of the timber member, A – coefficient that depends on the species of the tested sample, $R^{0,5}$ – value of the force [N].

For structural timber, the reduction factor δ is in the range 0.5–0.8, depending on the defectiveness of the element. Three separate values of δ were originally proposed according to the presence and size of defects measured on the visible faces of the timber element. Criteria for the measurements of the defects can be deduced from the UNI 11119:2004 [1], for the visual grading of structural timber on site (see Table 2).

Concerning the coefficient A, the values proposed are $A = 350$ for Silver fir (*A. Alba*, Mill.) and Larch (*Larix decidua*, Mill.) at a moisture content in the range of 12–14%. For Chestnut (*C. sativa*, Mill.) a value of $A = 263$ was proposed [35]. The experimental force R usually ranges from 700 to 3000 N, and is determined from the linear part of the force-penetration plot.

Finally, in order to adjust the value of $E_{0,\mathrm{mean}}$ for different values of moisture content, the result must be divided by a correction factor C [35]:

$$C = (1 - 0.0079 \cdot \Delta_{u-15}) \tag{4}$$

where Δ_{u-15} is the difference, in percentage, between the moisture content u of the sample (below 25%) and the reference moisture content at 15%.

7.2. Limitations

Hardness generically refers to a property of solid materials that offers resistance to various kinds of deformation when an external force is applied. The test method reported here refers to a specific indentation hardness test, i.e., the resistance to plastic deformation due to a constant load. Several different factors influence the hardness measurement of wood, such as anisotropy, heterogeneity, moisture content, and obviously the shape and size of the object applying the force. For wood, there is no simple relationship between the results of different hardness tests. The device here proposed, i.e. the 10 mm diameter hemispherical bit, was chosen among various alternate shapes in order to obtain the best results if applied on historic timber, especially in terms of test repeatability. Hardness measurements are also dependent on the surface orientation (end- or side-hardness) of the wood.

The method is very sensitive to the state of the selected test area, which must be clear, without visible defects or biotic attacks. Wood hardness is inversely proportional to the moisture content. For softwoods, hardness values of air dry samples are

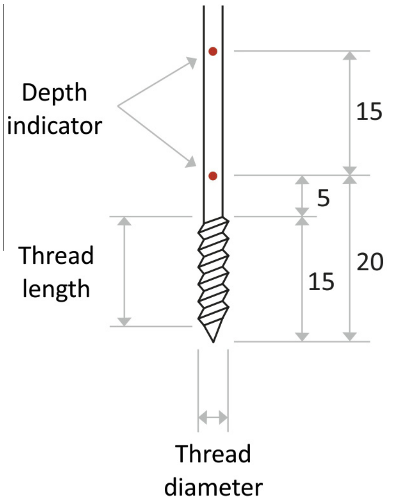


Fig. 34. Short thread of the probe.

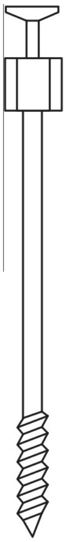


Fig. 35. Probe with double heads.

Fig. 36. Tool for withdrawal measurement.

approximately 1.7÷1.8 higher than for green samples. Also this condition must be taken into account when selecting the test area.

7.3. Application

The method has been successfully used, since the 80s [36], for the investigation of mechanical properties of timber elements, combined with other NDT methods in a number of cases. Examples of applications, together with several comparisons with other NDT methods, can be found in: reference [37], regarding the queen-post trusses of "Teatro Sociale" of Trento (Italy), reassembled in the Laboratory of University of Trento (Figs. 30 and 31); reference [38], regarding the trusses of "Teatro Zandonai" of Rovereto (Italy) (Fig. 32); reference [39], regarding on site non-destructive tests on a timber bridge in Val Cadino (Trento, Italy) (Fig. 33).

7.4. Summary

The hardness test proposed by Piazza and Turrini [36] is a modified Janka hardness test, based on the force required by static loading to embed a steel hemisphere completely into a wood surface. The result of the hardness test described here is the load *R* for obtaining the given penetration of the given steel pin. The test can be easily applied on site for existing timber elements, by indenting the lateral surfaces of wood, orthogonal to the grain direction. Using appropriate correlations, it is possible to obtain a first evaluation of the longitudinal modulus of elasticity of timber member.

7.5. Recommendations

It is recommended to choose parts of a timber surface without defects or biotic attacks. It is recommended to average the results obtained from two tests for two opposite longitudinal faces, repeated at 1/3 and 2/3 of the beam span. It must be underlined that each test consists in five measurements taken in a limited portion of the element. The result of one test is obtained by averaging the three median values among the five measures.

As already mentioned, hardness is sensitive to the moisture content. Consequently, moisture content should be measured in the same areas where hardness tests are carried out, as the value of hardness decreases with increasing moisture content. Simple resistance (pin type) electric moisture meters can be used. The equation given (Table 2) was found for wood with moisture content between 12% and 15%.

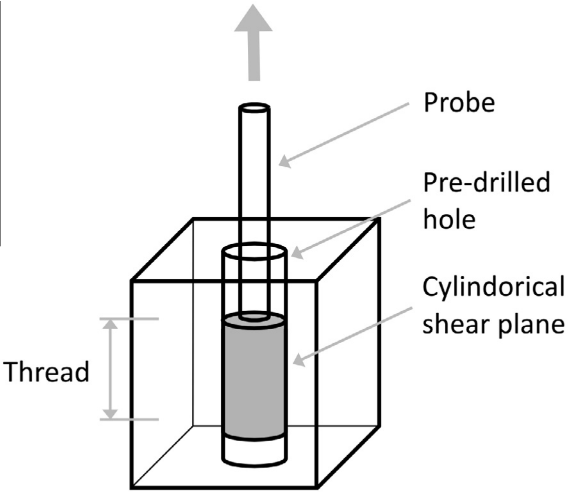


Fig. 38. Cylindrical shear plane around probe thread.

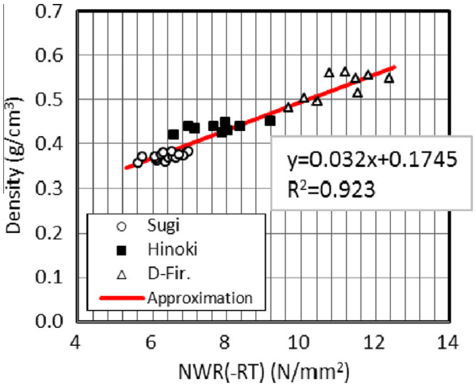


Fig. 39. Densities-NWR (−*RT*) relationships.

8. Shear strength of screw withdrawals

8.1. Testing methodology

Screw withdrawal measurement is a semi-destructive testing method which is able to estimate physical/mechanical properties of timber such as their densities and also shear strength both of

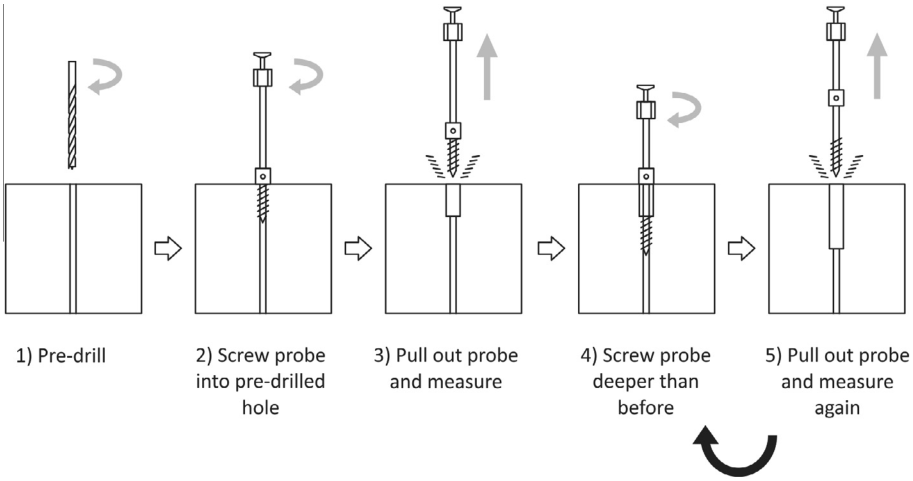


Fig. 37. Coaxial multiple withdrawal resistance (CMWR) measurements.

perpendicular and parallel to the grain. Distribution of properties along the depths of timber is obtained from coaxial multiple withdrawal resistance measurements. Screw withdrawals are described in detailed inspections of existing timber structures using commercially available wood-screws [40]. For this novel method new metric-screw type probe with short-threads was developed [41]. Thread shape of these metric-screws is standardized by ISO 261 and 724. The short-threads of the probe turns more accurate to set the measuring depths in timber, and also to reduce withdrawal forces. The metric-screw probes have cylindrical shear planes around the threads. As timber is anisotropic, these cylindrical shear planes have shear strengths correspond to their withdrawal directions. Fig. 34 and Fig. 35 show the probes for the screw withdrawal measurements which have short-threads. These probes are manufactured from metric threaded-rods. Diameter, pitch and length of the probe thread in Figs. 34 and 35 was 3.87 mm, 0.7 mm and 12.85 mm respectively. The probe has double heads of conical shape on top and hexagonal heads below for withdrawing and screwing respectively. The withdrawal tool is shown in Fig. 36. The load-cell is installed in the tool. Peak loads are indicated on the indicator connected to the load cell. Metric-screw type probes need pre-drilled holes for screwing them into timber. In order to measure accurate withdrawal resistances of timber using metric-screw type probes, pre-drilled holes with precise diameters and orthogonal to the surfaces of timber are required. Diameter of the pre-drilled holes used with the probes shown in Fig. 34 was 3 mm. Single withdrawal resistance (SWR) measurements are used for typical withdrawal measurements. The probes are screwed into timber. The probes are able to be screwed into timbers through finishing such as gypsum boards and plaster, etc.

Metric-screw probes have longer and smaller diameters of threads than those of typical wood-screws. Long probes are able to measure withdrawal resistances in deep of timber. Coaxial multiple withdrawal resistance measurements (CMWR) using long metric-screw type probe provide distributions of withdrawals along pre-drilled holes. Screw withdrawals can provide distribution of withdrawals along the depths in timber. Fig. 37 illustrates procedures of CMWR using the same pre-drilled hole. Typical procedures of CMWR are as follows. The probe is screwed into timber 20 mm deep. The probe is pulled out and withdrawal-resistances are measured simultaneously by the withdrawal tools. The probe is removed from the hole to get rid of sawdust from the hole. The probe is screwed 15 mm deeper than before. These procedures are repeated. Tip positions of the probes in timber will be every 15 mm such as 20, 35, 50 mm in depths.

Measured withdrawal resistances are affected by the area of outer cylindrical shear plane around the probe threads. Removing the effect of dimensions of the probe threads, measured withdrawal resistances were normalized by the outer cylindrical area of the thread. These normalized withdrawal resistance (NWR) is obtained by formula (5) [42]. NWR indicates estimated shear strength of timber on the outer cylindrical shear plane shown in Fig. 38. When the probe is screwed into the timbers from their longitudinal surfaces (LR and/or LT planes), the direction of the estimated shear strength (NWR) will be RT-direction (radius and/or tangential direction = perpendicular to the grain) of the timber.

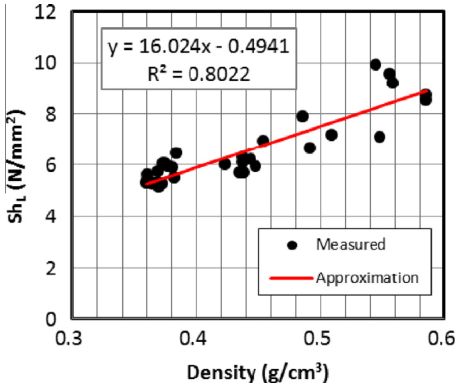


Fig. 40. Densities-shear strength (*L*) Sh_L relationship.

$$\tau = \frac{P}{R_t \cdot \pi \cdot L_t} \quad [\mathrm{MPa}] \tag{5}$$

where τ – estimated shear strength (NWR) [N/mm^2], P – withdrawal resistance [N], R_t – diameter of the thread (peak to peak) [mm], L_t – length of the thread of probes [mm], π – circular constant.

Single withdrawal resistance (SWR) measurements are used for typical withdrawal measurements. The relationship between densities and NWR ($-RT$) using metric-screw probes by SWR tests are shown in Fig. 39 [43]. The tests used sound timber specimens of three coniferous species. NWR ($-RT$) means NWR for radial (R) and/or tangential (T) directions of timber, those are for perpendicular to the grain directions. A regression formula between density and withdrawal strength is proposed in formula (6). Regression coefficients a_1 and b_1 of the formula (6) are 0.032 and 0.1745 respectively in Fig. 39. These regression coefficients are obtained using three coniferous species totally. Withdrawal measurements are applied perpendicular to grain in general, NWRs obtained from these withdrawal measurements are perpendicular to the grain direction. There are some differences between NWRs and typical shear strengths. Typical and nominal shear strengths listed in typical wood handbooks are shear strengths parallel to the grain, but NWRs are those for perpendicular to the grain. Typical shear strengths are those on flat shear planes, but NWRs estimated from withdrawals are shear strengths on cylindrical shear planes. Fig. 40 shows relationships between density of timber and measured shear strengths (L) Sh_L parallel to the grain by standard shear tests (ASTM D143, JIS Z2101) [43]. A regression formula between strength (L) Sh_L and density is proposed in formula (7). Regression coefficients a_2 and b_2 of formula (7) are 16.024 and −0.4941, respectively in Fig. 40. These regression coefficients are obtained using three coniferous species. Shear strengths (L) Sh_L are able to be calculated from NWRs of withdrawal resistances using formula (8) and these regression coefficients a_1, a_2, b_1 and b_2.

$$D = a_1 \cdot \mathrm{NWR} + b_1 \tag{6}$$

$$Sh_L = a_2 \cdot D + b_2 \tag{7}$$

$$Sh_L = (a_1 \cdot a_2) \cdot \mathrm{NWR} + (a_2 \cdot b_1 + b_2) \tag{8}$$

where a_1, a_2, b_1, b_2 – regression coefficients, D – density [g/cm^3], NWR – normalized withdrawal resistance [N/mm^2], Sh_L – shear strength [N/mm^2].

8.2. Limitations

This is a SDT method and so visual appearance is slightly affected by the holes made in timber. Screw withdrawal measurements with pre-drilled holes are more time consuming than those without pre-drilled holes. Also CMWR measurements are more time consuming than SWR. Screw withdrawal measurements need precise diameter of the pre-drilled holes. Lengths of the pre-drilling holes and depth of the withdrawal measurements are limited by the length of the drills and probes. Knots are often hidden in timber objects. These defects are generally very hard and often make pre-drilling difficult to apply. When the probe is in

(a) Overview of timber house **(b)** Measurement of timbers in bathroom

Fig. 41. Measurement of timber house in Saitama Prefecture.

Fig. 42. Measurement of timber roof frames in Tsukuba City.

and around the knots, it provides very large withdrawal resistances. These areas should be avoided (outlier values) since it affects the mean values of measured withdrawal strength and precision of the method. In order to obtain reliable results from SWR measurements, multiple SWR measurements of the object are required. Reliable distributions of withdrawals in timber need multiple CMWR measurements of the object.

8.3. Application

Screw withdrawals using wood-screws were used for the evaluation of fire-retardant-treated timber during 1990s in U.S. Screw withdrawals have been used to estimate density commonly; density is applied for the prediction of dynamic modulus of elasticity using stress wave NDT methods. Examples of screw withdrawal measurements in Japan are shown in Fig. 41(a) and (b) and Fig. 42. Fig. 41(a) shows timber house constructed 60 years ago in Saitama Prefecture, Japan. Fig. 41(b) shows measurement of timbers in the bathroom. Timbers around bathrooms are often deteriorated by the moisture and leaked water from the bathroom. Fig. 42 shows measurement of timber roof frames exposed outside more than 20 years in Tsukuba City, Japan. This timber roof frame was used for the durability study of traditional roof material (thatch) for the periodical reconstruction of “Grand Shrine of Ise” in Mie Prefecture, Japan.

8.4. Summary

Screw withdrawal measurement is a simple semi-destructive testing method using small holes applied in timber. Screw withdrawals are available in detailed inspections of existing timber structures, since it is able to estimate physical/mechanical properties of timber such as density and also shear strength both of perpendicular and parallel to the grain. For this method, new metric-screw type probes with short-threads were developed. Measured withdrawal resistances are normalized by the outer cylindrical area of the thread. These NWR indicates estimated shear strength of wood on the outer cylindrical shear plane. Densities and shear strengths parallel to the grain of timber are estimated from NWRs. This estimation need regression coefficients obtained from experiments. Distribution of properties along the timber depths is also obtained from coaxial multiple withdrawal resistance (CMWR) measurements. Properties estimated from these screw withdrawals can be used for integrity indexes and structural calculations of existing timber structures. These results are applied for the evaluation of the existing timber structures.

8.5. Recommendations

Screw withdrawal measurements need orthogonal pre-drilled holes to the object surface with constant diameters along depth. Drill guide assist applying orthogonal pre-drilled holes. After

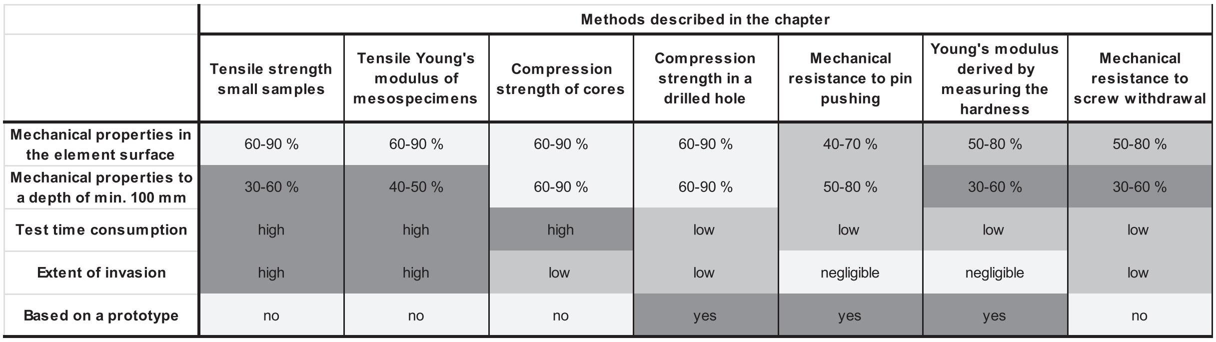
Table 3
Correlation coefficients between SDT predictions and mechanical and elastic properties when compared with standard test methods.

SDT methods	Mechanical properties and elastic properties					
	Clear wood					Structural timber
	Tension		Tension		Shear	Bending
	f_t	E_t	f_c	E_c	f_y	E_m
	Tensile over small samples*	Tensile over small samples*/tensile over mesospecimens	Compression over cores/compression in a drilled hole		Screw withdrawal	Hardness test
	1	1/0.75	0.77–0.96/0.92	0.89/0.87	0.89	0.45

f – strength; *E* – modulus of elasticity; *t* – tension; *c* – compression, *v* – shear, *m* – bending.

[*] This results is claimed since the dimension of the small samples is similar to standard tests.

Table 4
A synoptic table describing the success rate of prediction of mechanical properties, the time consumed and the extent of invasive damage caused by the presented methods.



	Methods described in the chapter						
	Tensile strength small samples	Tensile Young's modulus of mesospecimens	Compression strength of cores	Compression strength in a drilled hole	Mechanical resistance to pin pushing	Young's modulus derived by measuring the hardness	Mechanical resistance to screw withdrawal
Mechanical properties in the element surface	60-90 %	60-90 %	60-90 %	60-90 %	40-70 %	50-80 %	50-80 %
Mechanical properties to a depth of min. 100 mm	30-60 %	40-50 %	60-90 %	60-90 %	50-80 %	30-60 %	30-60 %
Test time consumption	high	high	high	low	low	low	low
Extent of invasion	high	high	low	low	negligible	negligible	low
Based on a prototype	no	no	no	yes	yes	yes	no

The most favorable rated parameters are marked lightest color and the least favorable parameters indicates the darkest color.

drilling the holes, saw dust remaining in the pre-drilled holes should be removed by handy rubber blower, etc. Slow screwing of the probe is recommended. Constant rate and slow withdrawing is recommended for the measuring of accurate peak withdrawal resistances. Some of the latest electric screwdrivers are available for slow withdrawing. When pre-drilled holes are applied to the end of timber, the thin drill is often guided into the earlywood between the annual ring. These withdrawals of the probe provide less withdrawal strength than that perpendicular to the grain.

9. Conclusion

From all the NDT and SDT methods available, few (e.g. visual grading and proof-loading) can be considered standalone methods. The choice for the application of a particular NDT or SDT method usually results from the need to confirm the first information obtained from visual grading.

Either by extracting small volumes of wooden material to be prepared and tested in the laboratory or by making the test in situ the SDT methods described in the present paper is considered as increasingly important in the evaluation of timber structural members. Their importance came from the opportunity to obtain a direct reading of a mechanical property of a timber member. Moreover, since NDT are based on empirical models (e.g. regression curves) very dependent upon the testing setup (including wood species, type of equipment and operation parameters, moisture content of wood), the question about the validity of using these equations to a new situation (new timber structure) is not easy to answer. In this respect, SDT methods can also have an important role in the validation of NDT results.

The success rate of prediction of mechanical properties, the time consumed and the extent of invasive dam-age caused by the presented methods are compared in Tables 3 and 4.

Table 3 acknowledges the capability of tensile, compression and screw withdrawal to provide a confident prediction of the mechanical and elastic properties of clear wood zones. However, as the hardness test shows the integration of information from defects leads often to a significant decrease in the level of confidence of the prediction. Since the modulus of elasticity is generally more affected by clear wood properties than by the effect of local weak zones [44], SDT methods, as described, can provide a confident prediction of the global modulus of elasticity of structural members.

Comparing all tests, there are some similarities between them. All of them are local test methods meaning that the results (strength and modulus of elasticity) can be highly variable depending on the selection of suitable places for sampling and the number of samples taken. In these respects the influence of early- and latewood alternation in annual rings (for all methods) and the way the test is carried out should always be taken into consideration. Comparing both tensile SDT methods the one using mesospecimens [13] derived from the first one [7] having in mind the extraction of smaller volumes of wood and that the extraction process could be simpler and easier. However these methods show still a more intrusive character compared to the other methods presented here. Some methods can be considered as multifunctional, like the compression strength of cores, being the cores also suitable for wood species identification, dendrochronology, visual assessment of growth rings and measuring of protective agent penetration.

Compression in drilled holes, mechanical resistance to pin pushing, hardness test and screw withdrawal show as advantage as regards the other methods the possibility to analyze the tests results in situ (real-time data). This situation turns more efficient the survey work. Therefore it is possible to make the decision onsite to conduct additional tests (same method or combination to others) contributing to a more reliable prediction of mechanical and elastic properties of structural timber members. These methods also are less time consuming given the fact that they do not need time to prepare special test pieces for testing at the lab.

Compression in a drilled hole, pin pushing and screw withdrawal all show the capacity to analyze a substantial or complete (pin pushing) portion of the cross-section. The remaining SDT methods only analyze the timber surface (up to around 40 mm) and thus more careful analysis should be performed considering the expected variability inside the timber cross-section.

Finally, the reliability of all methods, just like the majority of NDT and SDT methods applied for timber diagnostics, depend heavily on the variability of internal factors, moisture content and wood species and wood treatments.

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