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Review

In situ assessment of structural timber using the resistance drilling method – Evaluation of usefulness

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HIGHLIGHTS

- Resistance drilling method is useful to estimate the depth of wood decay in timber structures.
- Resistance drilling method should be treated as a qualitative assessment rather than a quantitative one.
- Testing has a point focus and so making responsible estimates of timber properties requires many measurements.

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ABSTRACT

The paper presents a survey of the state-of-the-art of the application of drilling resistance methods as quasi non-destructive (semi-destructive) diagnostic techniques for testing timber structures, with examples of their application. The method is based on correlating drilling resistance and hardness – density of materials. Resistance drilling tests are quasi non-destructive as the openings arising from drilling do not affect the mechanical and aesthetic properties of the material being tested. The average diameter of an opening remaining after testing does not exceed 3 mm. The method enables assessment of the extent of wood damage of the tested elements and a preliminary assessment of the mechanical properties based on an appraisal of internal defects (e.g. wood decay) in the material. The paper presents also research using a mobile drilling resistance device carried out by the authors to investigate the technical state of buildings, including those of high historical value.

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1. Introduction

Actions aimed at conserving and strengthening historical timber structures are often undertaken without detailed diagnosis of what caused damage. Renovations and interventions in the historical building substance are carried out most often on the basis of analyses of interventions in comparable structures. Researchers, engineers, conservation specialists are overly reliant on intuition when carrying out repairs and strengthening, which can translate into unjustified solutions on economic grounds, mistakes and exceeding the specifications required for strengthening. An accurate diagnosis, which is most important in the conservation of historic buildings, must address in detail the technical condition of structural elements. Testing methods for timber structures can be divided into three types: destructive, semi-destructive (SDT) and non-destructive (NDT).

Wood construction elements are characterised by a large load bearing capacity and stiffness in relation to their own relatively low weight. As a natural material, wood is very sensitive to moisture and damage by biological agents and is characterised by lack of homogeneity. The most common defects in structural timber elements include: flaws in material – slope of grains, knots, shakes and burls, defects due to fungi – stains and rots, defects due to insects, defects due to over-loading – timber cracks, structural failure of members and joints, excessive deflections [1]. The lack of homogeneity in timber translates also to different strength values both in relation to the direction in which fibres have grown in the trunk of the tree, and also to variations in the wood material in terms of its physical and mechanical parameters (density, presence of knots, cleavages). The EN 338:2009 standard [2] defines wood class in relation to specific values describing mechanical properties. These are taken to refer to the whole structure, but in reality for the reasons cited above, parameters of specific structural elements differ from one another [3]. It is important to note, that aside from lack of homogeneity, in the case of historic wooden structures, a number of additional factors influence the mechanical properties of the wood: moisture changes, temperature changes, impact of biological agents and the duration of use of the structure.

The guidelines included in [1] indicate that the appropriate strength grading of timber is one of the most important aspects identified in a detailed survey of timber structures. In order to allocate a wooden structural element to one of the strength classes set out in the EN 338:2009 standard, it is necessary to have ascertained its physical and mechanical properties, such as modulus of elasticity, bending strength and wood density [4]. Assessment of these three timber properties is especially important as overestimation of wood class can result in failure of the building structure, whereas underestimation results in over-sizing of new elements and structural strengthening and unnecessary replacement of historic timber elements with new ones in order to avoid insufficient load-bearing capacity.

One method for assessing wood quality is destructive testing. In the case of historical buildings, extracting samples is as a rule impossible on account of the building character, which is why analysis needs to be based on non-destructive and quasi-destructive testing [5]. Moreover, an additional problem is that interpretation of test results carried out on small wood samples is problematic [6]. When using the NDT method, obtaining qualitative results (extent of possible damage, structural discontinuities etc.), as well as quantitative results (density, resistance, modulus of elasticity) from non-destructive testing requires carrying out non-destructive tests alongside destructive tests on samples taken from structural elements. Correlation of results obtained from non-destructive and quasi-non-destructive and wood strength testing generates system-wide data for carrying out static analysis of timber structures. Appropriate interpretation of results enables the formulation of parameters to be adopted as appropriate solutions for strengthening and conservation of heritage timber structures.

Non-destructive and quasi-non-destructive testing include research on: identifying the mechanical and physical properties of materials and structural elements, identifying flaws and discontinuities in materials, measurement of the geometric dimensions of building structures without interfering with the continuity of their structure or influencing their functional properties. The features, which distinguish the NDT method are: mobility, possibility of testing in a variety of field and atmospheric conditions and much lower costs when compared to more traditional approaches, which are a function of the type of measurement equipment used and analyses carried out. A key factor is also assuring safety of both the structures being tested and the persons operating the measurement equipment.

The most common flaws appearing in timber elements include internal damage and discontinuities. It is important to emphasise that these are difficult to identify as often there are no signs visible on the external material surface until significant damage has taken place. According to [7], 30% of flaws and damage in timber arises internally in structural elements, and so these are impossible to determine through visual assessment methods. Testing timber structures using NDT and SDT methods causes minimal damage to the surface of the elements while at the same time providing information about timber quality inside the structure.

The application of non-destructive testing is especially important in regular monitoring of the structural condition of an heritage building when it is in use. Regularly repeated measurements carried out in specified locations, especially in sensitive areas (e.g. corners, which are susceptible to the impact of damp) in the structure enable identification of threats, which can cause damage suddenly or lead to the destruction of structural building elements. Such threats include structural wood damage caused by for example by insects infesting the wood or by the presence of fungi. The variety of NDT-tools can be used to estimate the extent of such threats and to assess if they are intensifying over time. In addition, such regular monitoring allows for comprehensive, continuous assessment of the condition and function of historical structures. Such actions contribute to assuring the safety of users, helping to preserve the historical and artistic values of buildings and providing for checks, assessments and audits of technical solutions used to date to preserve such sites.

Among non-destructive and quasi-non-destructive tests used to assess and diagnose timber structures, the most common are methods and techniques presented in Table 1, and which are described in detail inter alia in [5,8–14]. Non-destructive and quasi-non-destructive methods can be categorised into two groups: global test methods (for example visual evaluation, ultra-

Table 1
Selected methods available for assessing timber in building structure.

Organoleptic methods	Acoustic methods	Quasi-non-destructive (semi-destructive) methods	Radiographic methods
Visual evaluation	Stress waves	Resistance drilling	X-rays
Acoustic evaluation	Ultrasonic technique	Core-drilling	Gamma rays
Fragrance evaluation	Acoustic emission	Screw withdrawal	
		Hardness tests	
		Needle penetration	
		Pin pushing	
		Tension microspecimens	

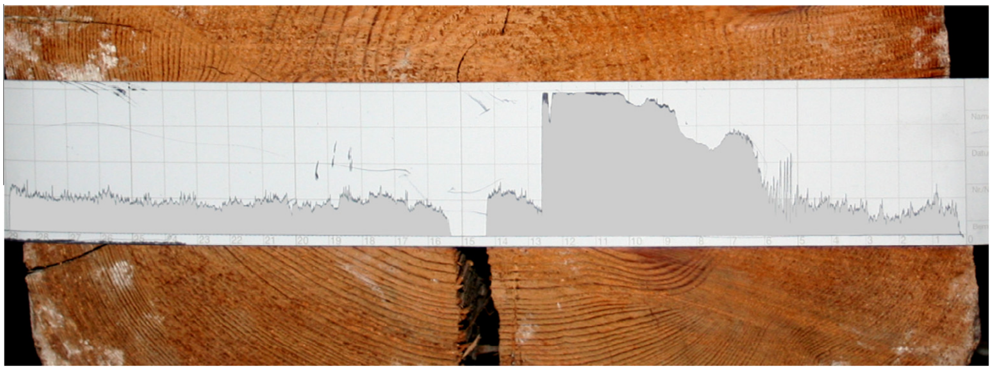

Fig. 1. Example of a graph showing drilling resistance registered on wax paper (the field under the graph in the photograph has been darkened additionally).

sonic and stress wave techniques) and local test methods (for example drill resistance method, core-drilling, pilodyn method) [15].

The goal of this paper is to provide a detailed analysis and systematic review of the current state of knowledge related to the resistance drilling method, which is also referred to as the resistographic method (the term resistograph is a trade name protected by the RinnTech company), which represents one quasi-non-destructive method for testing local wood properties in elements of a timber building structure.

2. Drilling resistance method

Mobile devices using the drilling resistance method involve drilling a small diameter (1.5–3.0 mm) with a steel needle into a timber element and measuring the resistance encountered as a function of penetration depth. The speed and rotation of the drill is constant. The turning moment required to maintain constant drilling speed is equal to drilling resistance and is registered graphically in relation to drilling depth (Fig. 1). Zones requiring a smaller turning moment are associated with lowered density. These are zones, which include areas of inner decay, empty spaces, cracks and fissures. Resistance drilling testing qualifies as a quasi-non-destructive method for assessing timber elements as the holes which result from drilling do not affect the tested element mechanically or aesthetically. The diameter of the drill-hole in the timber element resulting from the test does not exceed 3 mm and so is no larger than the exit hole of the *Anobium punctatum* – one of most common pests appearing in structural timber in Europe.

The shape of the resistance drilling graph in healthy material is strictly related to the difference in density of earlywood and latewood [16], the structure of annual growth rings and the angle of drilling. The most accurate graphs are obtained when the steel needle is introduced at a 90° angle in relation to annual growth rings with drilling in a radial direction [13,17]. The graph showing drilling resistance can be presented as a print-out or stored in electronic form. Graph peaks indicate high resistance and high density. Troughs and low points indicate low resistance and low density. Timber subjected to complete disintegration offers no drill resistance. In such a situation, the graph is a flat horizontal line. Knots and the like appear as peaks on the graph, but it is important to underscore that although they register as high drilling resistance and high density, they are not correlated to timber strength.

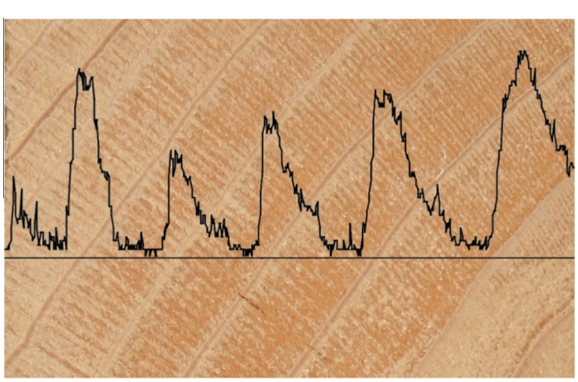

Fig. 2. Distribution of annual wood growth rings. Differences in density of earlywood and latewood are clearly visible.

Application of drilling resistance methods as field tests enables: localising internal damage and discontinuities in timber elements without affecting their functional properties [18]. It is possible to assess the extent of damage in the tested timber elements, inspect the state of timber covered by other materials (plaster, gypsum shells, walls, board covers etc.) without disassembly. Measurements need to be carried out in locations especially susceptible to weakening and biodegradation, such as for example: areas where wood connects with other materials (concrete, bricks), where wood contacts soil, in elements which are visibly damp or degraded or adjacent to door and window openings, as well as timber roof structures and attic spaces [19]. The drilling resistance method is also effective where assessment of timber condition in carpenter's joints is needed [20] and in the case of glued laminated timber. It is necessary, however, to note the differences the drilling resistance graphs register for specific lamellas [13]. It can be very difficult to interpret the differences, due to the density differences between them. Measurements of drilling resistance provide also for generating a graphical presentation of the distribution of annual growth rings [21,22] (Fig. 2).

There are many examples of the use of mobile devices to test the drilling resistance of wood in timber structures. There have also been efforts to correlate results obtained through drilling resistance testing with results of tests of timber strength, which aim to estimate the mechanical properties of timber in a structure. Results are presented in the form of graphs showing how relative resistance (*RA*) depends on drilling depth (*H*), which enables assessment of timber properties by correlating average values of the Resistance Measure (*RM*) to density, strength and modulus of elasticity [23]:

$$RM = \frac{\int_0^H RA \cdot dh}{H} \tag{1}$$

A device called the Resistograph was registered in 1993 by Rinn, a German researcher. According to [24], the Resistograph is excellent at revealing changes in density in timber caused by biological damage. Moreover, the effectiveness of the device in assessing timber density was confirmed through comparison with X-ray testing [25].

Approx. 10 different types of device for testing drilling resistance are currently available on the market [16]. They are characterised by different features, starting with diameter of the drill bit and its shape, through to the size and reach of the device, and finishing with the resolution and accuracy of results generated. It is worth underscoring that selection of the appropriate device for testing heritage buildings should not just be based on its cost. It is important to take into account drill bit diameter (1.5 mm is best), the possible drilling depth (minimum 30 cm due to the large cross-sections that characterise historic buildings), the possibility of recording measurements at an angle to the wood grain, battery performance (especially important in field research), the way results are registered (modern equipment provides for electronic storage of measurements) and also the precision and sensitivity of the device (high resolution and strong linear correlation with timber density, $r^2 > 0.8$).

3. Analysis of physical and mechanical properties of timber using drilling resistance testing

Numerous tests have been carried out to determine the correlation between results of drilling resistance testing and results of strength testing. As a result of testing described in [26], which sought to specify the dependencies between results of non-destructive testing and the strength properties of chestnut wood, the correlation between density, compressive strength and modulus of elasticity in compression along the grain and the *RM* value was determined to be $r^2 = 0.59 \div 0.70$ for new timber and $r^2 = 0.64 \div 0.68$ for historic timber sourced from demolition.

The same research team carried out tests to determine the correlation between results of non-destructive testing and compressive strength and modulus of elasticity in relation to the direction of the annual tree ring growth in the sampled cross-section: radial, diagonal and tangential [27]. The correlation obtained (for new and old wood) between the *RM* value and density was at the level of $r^2 = 0.36 \div 0.38$, the modulus of elasticity was $r^2 = 0.52 \div 0.67$, and compressive strength $r^2 = 0.47 \div 0.78$.

In [28], drilling resistance testing was carried out for old beech timber, which had been seriously damaged by wood worm, sourced from the disassembled structural ceiling of the Salerno Cathedral in Italy. Timber beams with a moisture content of 11–12% were subjected to testing. They were divided into seven segments and four bore holes were made in different directions in each one. Next, the beams were cut along the border of the divisions, creating eight elements of a thickness of 50 mm, from which samples were taken for density testing and determining compressive strength. As a result of the testing completed, graphs were generated to show the relationship between the *RM* value and density ($r^2 = 0.59$) and between density and compressive strength ($r^2 = 0.59$).

Tseng and Hsu [29] carried out drilling resistance testing and strength testing of wood from *Cunninghamia lanceolata*, in which samples were divided into groups according to the pattern of annual growth rings in the cross-section. The drill bit was introduced at 30°, 45° and 90° angles. The correlation between the *RM* value, density (max out $r^2 = 0.88$), modulus of elasticity in compression (max $r^2 = 0.57$) and compressive strength perpendicular to the grain (max $r^2 = 0.77$) was investigated. For this type of timber, the relationship between the *RM* as measured and the physical and strength properties was based strictly on the drilling direction and annual tree ring pattern in the samples. The best correlation between RM and density was achieved where drilling was perpendicular to the grain. This is because other angles of drilling are affected by friction.

In [30], results of non-destructive testing obtained through a variety of test methods were compared with results of strength tests of new spruce, fir and pine timber with 12% moisture content. A 2450p Resistograph was used to carry out testing using the drilling resistance method. Testing investigated the relationship between the *RM* value and the following: compressive strength along the grain ($r = 0.52$ spruce, $r = 0.59$ fir, $r = 0.64$ pine), compressive strength perpendicular to the grain ($r = 0.05$ spruce, $r = 0.08$ fir, $r = 0.48$ pine), modulus of elasticity in compression along the grain ($r = 0.33$ spruce, $r = 0.14$ fir, $r = 0.32$ pine) modulus of elasticity in compression perpendicular to the grain ($r = 0.37$ spruce, $r = -0.01$ fir, $r = 0.41$ pine), density ($r = 0.74$ spruce, $r = 0.65$ fir, $r = 0.75$ pine) and hardness measured using the Janka method in the diagonal direction ($r = 0.64$ spruce, $r = 0.44$ fir, $r = 0.57$ pine), radial direction ($r = 0.41$ spruce, $r = 0.35$ fir, $r = 0.65$ pine) and tangential direction. An analysis of the values cited above leads to the conclusion that the relationship between the *RM* value and the mechanical and physical properties of timber are strongly related to the tree species of the timber under investigation. The fact that a high correlation coefficient may be obtained for a given tree species does not mean that it will also apply in the case of different tree species. It is important to note that the correlation values obtained are not strong enough to be predictive. Moreover, tests carried out for clear specimens. Determining the correlation between mechanical properties and the RM value for on-dimension members may not be valid.

The research project [31] focused on determining the significance of non-destructive testing in the assessment of materials and structures of historic buildings with tests carried out in a systematic way in situ and in the laboratory for historic structures in Valencia. In the part devoted to timber structures, guidelines were provided for carrying out a correct assessment of technical condition and strength properties. Drilling resistance testing of the timber allowed assessment of the condition of the material structure and the extent of damage caused inter alia by insects. Analysis of results enabled estimation of the mechanical properties of the timber. The use of different NDT devices in field testing was recommended along with analysis of the results obtained, which often complement one another. This approach should be used as a basis for determining the relationship between them and making recommendations on the technical condition of the building structure. Moreover, it is important that prior to initiating non-destructive testing, the tree species is identified accurately, along with the moisture level, dimensions of the element, initial localisation of weaknesses, knots, rot and other features which may impact material quality.

In [32] it was determined that the indication of density obtained through resistance drilling equipment was very accurate. A close correlation between density and *RM* value ($r^2 > 80\%$) was determined on the basis of tests carried out for various tree species. It was noted, however, that testing was based only on a scatter of points. Moreover, the lack of harmonisation between resistance drilling equipment poses another problem, which requires separate calibration of each device. It is important to note that the authors indicate that the resistance drilling method should not be used to validate a structure as a whole because there are too many variables influencing the drilling resistance graph.

Research presented in [33] does not confirm the validity of using resistance drilling methods and other NDT techniques to assess the mechanical properties of historic timber structures. Testing made use of horse chestnut samples from a disassembled timber roof of a 19th century building in Naples. A series of non-destructive tests were carried out using resistance drilling to determine changes in density and to identify possible flaws and discontinuities internal to the elements analysed. Destructive tests were also carried out – compression applied along the grain and bending. Regression analysis was used to examine the relationship between results of NDT tests and tests of density and strength. A medium correlation was obtained between the density of the timber tested and results of resistance drilling tests ($r^2 = 0.55$ longitudinally and $r^2 = 0.51$ transversely), but the relationship was stronger when results were synthesised from different types of NDT testing (for resistance drilling, ultrasound methods and sclerometer testing $r^2 = 0.68$ for both directions). The strongest relationship between compressive strength along the grain and NDT testing results were obtained by bringing together drilling resistance testing and sclerometric testing ($r^2 = 0.68$ for both directions). The relationship between flexural strength and the average value taken from diagrams obtained from resistance drilling testing of the samples was also examined ($r^2 = 0.53$ longitudinally and $r^2 = 0.42$ transversely). According to researchers, the NDT test results are influenced by a variety of factors, e.g. moisture, number of tests, tree species of the wood tested, but their impact was not investigated in the research reported.

In [34] an attempt was made to assess strength properties of timber directly from measurements obtained from drilling resistance tests. The research involved using historic sweet chestnut timber from 18th/19th century beams, which were cut up into samples 450 mm long with a circular cross-section diameter of 240–260 mm. Measurements obtained from drilling resistance were carried out in a transverse and a longitudinal direction with respect to the grain. On-site it is not possible to carry out measurements longitudinally to the grain as the ends of the beam are embedded in the walls. It was shown, however, that the *RM* value received for measurements for both the transverse and longitudinal directions are convergent, which means that is sufficient to test only in one direction to obtain the information needed. In addition, destructive testing and drilling resistance testing was carried out for 20 cuboid samples ($50 \times 50 \times 100$ mm) of new fir timber. Based on an analysis of 120 measurements of drilling resistance along the grain, a correlation was obtained between the average *RM* value and compressive strength at a level of $r^2 = 0.58$. The research presented does not validate the application of the resistance drilling method for assessment of the mechanical properties of historic timber structures.

In [35], the authors describe application of the visual method to assessing the technical condition of timber structures. An attempt is made to correlate results of this method with results of non-destructive methods (testing using X-rays, ultrasound methods and resistance drilling methods) in order to answer the question of whether there is consistency between visual and NDT tests, and at the same time to check also whether the methods are appropriate and credible for assessing timber used in construction. Old timber from demolished buildings and new wood of the same species was used in the testing. The samples tested were conditioned at two different relative humidity (RH) values (0% and 70%), thanks to which the impact of moisture on the results of the non-destructive tests could be taken into account. It was shown that the average value of drilling resistance increases with increases in wood moisture, which has also been shown to be the case earlier [36]. However, it is important to emphasise that the higher drilling resistance of wood with high moisture content does not result from greater density, but from the friction caused by sawdust that remains in the drill hole. Typically, high moisture content wood (where the mass of both free and bound water increases the mass of wood) does not display higher mechanical performance. Despite the variety of NDT test results obtained in the research presented, using different methods does provide results, which can be confirmed additionally using the visual assessment method.

The analysis presented in [37] reports on the correlation of test results obtained from destructive and non-destructive methods applied to historic old chestnut wood. Wood samples with 10–12% moisture content were taken from the roof of an historical building in Naples and subjected to compression tests parallel to the grain and bending tests. Visual assessment concluded that the tested wood included a series of flaws: shape irregularities, knots, cracks, ring shakes, insect attacks. Samples were subjected also to non-destructive testing: sclerometric tests, ultrasonic tests, resistance drilling tests. The correlation between density and resistographic mean amplitude were determined as $r^2 = 0.55$ and $r^2 = 0.53$ for tests carried out in parallel and perpendicular to the grain. Based on the results of resistographic and sclerometric tests, a good correlation was obtained between the methods listed above and density – $r^2 = 0.64$ and $r^2 = 0.62$ for measures in parallel and perpendicular to the grain. Comparable results were obtained in an analysis of the correlation of the results of compression strength tests carried out in parallel to the grain and resistograph test results, as well as when using a combination of methods: resistograph and sclerometric testing ($r^2 = 0.54$ for tests in parallel to the grain, $r^2 = 0.23$ for tests perpendicular the grain, $r^2 = 0.68$ for resistograph tests in parallel to the grain and sclerometric tests perpendicular to the grain). Correlation between bending strength and resistographic mean amplitude was $r^2 = 0.58$ and $r^2 = 0.48$ respectively for testing in parallel and perpendicular to the grain. The main conclusion arising from these tests is that carrying out tests using a variety of non-destructive methods and a systematic analysis of all the results obtained, provides a basis for a more valid estimate of the density and mechanical properties of wood.

The conclusions arising from the testing described above are confirmed in [38]. Zhang et al. carried out both destructive and non-destructive testing (stress wave tests and micro-drilling tests) of larch wood. Analysis of results obtained from just one method indicated a weak correlation between the results of NDT tests and destructive tests (relationship between micro-drilling resistance and: modulus of elasticity with a correlation coefficient $r = 0.38$, modulus of rupture $r = 0.36$, compression strength $r = 0.49$). When results from stress wave tests and micro-drilling tests, were analysed together, the correlation is much higher between the results of NDT methods and results of destructive methods ($r = 0.71$ for modulus of elasticity, $r = 0.55$ for modulus of rupture and $r = 0.69$ for compression strength).

As the drilling resistance is correlated to density, which is often used to predict the mechanical properties of timber elements, Morales Conde et al. [39] examined the correlation between values for density of small-diameter wood cores (Ø = 7 mm) and drill resistance data. For depths of up to 20 mm (the external timber layer), a strong correlation was obtained at the level of $r^2 = 0.70$, however, the correlation for the whole element was lower than 0.5 (due to changing density of wood in the cross-section and higher friction on longer perforations).

In [40], the authors express doubt that timber strength properties can be assessed using drilling resistance methods. This is because the results of drilling resistance tests are influenced by many parameters, inter alia: wood moisture, sharpness of the drill bit, the angle and direction of drilling. For this reason, the main goal of applying this method is not assessment of the mechanical properties of timber, but verification of information obtained from application of other non-destructive methods. According to the authors, drilling resistance testing allows for an initial estimation of the mechanical properties of timber based on assessment of defects internal to the material tested.

In [41], methods of non-destructive tests (drilling resistance, ultra-sound and needle penetration testing), traditional visual tests and to a small degree destructive testing are presented as approaches to assessing mechanical properties of timber structures in heritage buildings. Preliminary laboratory testing was carried out using NDT methods on samples of historic pine timber obtained from rafter beams. The measurements indicated a relationship between *RM* values of measurements obtained from drilling resistance tests and from needle penetration. An influence of the distribution of annual growth rings on the results obtained was observed. No relationship was found between *RM* and the dynamic modulus of elasticity indicated by means of ultrasound tests. Field research is also described involving a timber roof structure and structural ceiling of a 16th century building. Thanks to drilling resistance testing, it was possible to estimate the extent of damage to the timber, the location of which had been identified through visual assessment. The results provided only for a qualitative assessment of the timber elements analysed. The mechanical properties of the timber tested was described using ultrasound tests, which delineated the dynamic modulus of elasticity.

Another study [42] failed also to find a correlation between measurements of timber density and *RM* values. It was determined that measuring drilling resistance indicates the location and extent of imperfections and discontinuities in timber. But due to lack of uniformity in the material structure (knots, slope of grain, localised damage, biological damage), it is not possible to assess the physical and mechanical properties of the timber using the drilling resistance method.

Tests of old and new full-scale wooden perlins presented in [43] found only a weak correlation between measurements of drilling resistance and the modulus of elasticity (*MOE*).

In [44], the justification for using non-destructive and quasi-non-destructive methods to assess the technical condition of the wood bridge in Dietfurt in Germany was investigated. The structure was taken out of use due to structural damage caused by insect infestation and overly damp timber. Visual inspection of the bridge and drilling resistance testing carried out on-site provided a basis for localising areas of significantly reduced density and identification of elements for replacement. Strength testing was also carried out and a series of NDT testing in the laboratory on samples taken from the structure. A comparison of results obtained from different testing methods, led the investigators to conclude that drilling resistance testing allows only for location-specific estimation of interior wood damage and changes in wood density. They are not useful in estimating the modulus of elasticity to bending or determining the load bearing capacity of joints. The drilling resistance method, along with the traditional method of visual assessment, was recognised to be a useful tool for generating indications of quality in tests of timber structures. According to the researchers, to obtain quantitative results, it is necessary to make use of other NDT techniques (e.g. stress wave technique) and destructive testing.

In case study [45], an assessment was carried out of the biological decay of structural timber elements in an ancient hayloft in Trento, Italy. Following determination of the wood species used in the structure and its moisture content, resistographic tests were carried out using a Resi B400 IML device. In this case, the resistance drilling method led to detection of wood decay caused by insects and fungi and provided an assessment of the extent of damage and degree of advancement. The analysis proved essential in assessing the structural status of the building and provided essential information for planning conservation work on the building structure.

In [46] results are presented of research on the impact of changing strength of Scots pine on static bending resulting from white rot decay *Tinea versicolor* (approx. 50% reduction in strength with a 7% loss of mass) and brown rot decay *Coniopora puteana* (approx. 50% reduction in strength with a 20% loss of mass). Drilling resistance tests indicate a lack of relationship between drilling resistance and degree of wood rot decay. According to the author, the method provides only results suitable for comparative analysis.

A practical application of using drilling resistance methods is assessment of the technical condition of beams in a medieval timber roof structure of the Tocnik Castle in the Czech Republic is presented in [47]. In this case, the drilling resistance method corresponded well to the method measuring speed of an ultrasound wave travelling through the wood and X-ray measurements. Analysis of the graphs generated by means of drilling resistance revealed biodegradation inside the structural elements caused by fungi.

In [48], research is presented on the technical condition of the timber structure of an historic 14th century church of St. Agatha in Sicily, which was obtained using drilling resistance and sonic tomography methods. The two methods complement each other in a very good way. Measurements from the acoustic tomograph enabled identification of zones of reduced density related to internal wastage and rotting. Thanks to drilling resistance measurements, information was obtained as to the degree of damage in these zones.

In [49], the authors present the use of a mobile device using the drilling resistance method to carry out a qualitative assessment of the technical condition of timber beams in the historical 19th century tower of Fort Snelling in Minnesota. To take measurements in critical areas which provide support for the rafter beams – at the interface of timber and brick – drill holes were made at a 45° angle to the beam surface. On the basis of the results, recommendations were made relating to the bad technical condition of the structure. Conservation of damaged elements was commissioned based on the drilling resistance graphs, which identified weakened and degraded zones in the material.

Mobile resistance drilling devices are used increasingly to assess the technical condition of timber in building structures, including heritage buildings, where the quasi-non-destructive character of testing is especially significant [50–56]. Thanks to an adapter, the device can be used to take measurements at a 45° angle, which facilitates, for example inspection of beams embedded in walls.

The results of assessments using drilling resistance applied to different types of samples do not provide an unambiguous answer to the question – which drilling resistance method is most useful for assessing the properties of timber in building structures (Table 2). Research conducted to date is not conclusive on this topic and the methodology relating to procedures and interpretations of results generated through drilling resistance techniques still needs more attention. The device enables identification and localisation of flaws and discontinuities internally in the material in a way that does not impact its structure or functional properties. Moreover, it provides for an initial assessment of the mechanical properties of the timber. In [57], the authors draw attention to the fact that assessing the strength properties of timber demands a high level of education and experience, which is why appropriate training is needed prior to applying resistance drilling. A review of the literature cited above leads to the conclusion that due to the lack of homogeneity of natural wood material, the resistance drilling method allows only for estimation of localised physical and mechanical properties of a wooden structure and does not provide a basis for assessing the building structure as a whole.

4. Dendrochronology and testing wood condition

On-site research focusing on historic timber structures should not focus exclusively on identifying flaws and localising discontinuities in materials. Dendrochronological testing should play an important role in assessing the technical condition of a building structure. Dendrochronology is a scientific method used for dating natural features, heritage structures and archaeological findings which contain wood. It is based on analysis of annual growth (tree rings), the width of which depends mainly on the environmental conditions that prevailed at a specific time. Annual growth generates a sequence, which varies in thickness (in years in which envi-

Table 2
Selected research on the correlation between *RM* values and the physical and mechanical properties of timber (NW = new wood, OW = Old Wood).

Research investigators	Wood species	Correlation		
Feio et al. [26]	Chestnut (*Castanea sativa* Mill.)	*RM* – density	$r^2 = 0.71$	NW
			$r^2 = 0.68$	OW
		RM – longitudinal modulus of elasticity	$r^2 = 0.60$	NW
			$r^2 = 0.64$	OW
		RM – longitudinal compressive strength	$r^2 = 0.59$	NW
			$r^2 = 0.64$	OW
Lourenço et al. [27]	Chestnut (*Castanea sativa* Mill.)	*RM* – transverse modulus of elasticity	$r^2 = 0.52–0.61$	NW
			$r^2 = 0.56–0.67$	OW
		RM – transverse compressive strength	$r^2 = 0.47–0.73$	NW
			$r^2 = 0.63–0.78$	OW
Ceraldi et al. [28]	Beech (*Fagus sylvatica* L.)	*RM* – density	$r^2 = 0.60$	
Tseng and Hsu [29]	*Cunninghamia lanceolata*	*RM* – density	$r^2 = 0.22–0.88$	
		RM – transverse modulus of elasticity	$r^2 = 0.04–0.57$	
		RM – transverse compressive strength	$r^2 = 0.22–0.77$	
Kloiber et al. [30]	Spruce	*RM* – density	$r = 0.74$	
		RM – longitudinal modulus of elasticity	$r = 0.33$	
		RM – transverse modulus of elasticity	$r = 0.37$	
		RM – longitudinal compressive strength	$r = 0.52$	
		RM – transverse compressive strength	$r = 0.05$	
	Fir	*RM* – density	$r = 0.65$	
		RM – longitudinal modulus of elasticity	$r = 0.14$	
		RM – transverse modulus of elasticity	$r = 0.01$	
		RM – longitudinal compressive strength	$r = 0,59$	
		RM – transverse compressive strength	$r = 0.08$	
	Pine	*RM* – density	$r = 0.75$	
		RM – longitudinal modulus of elasticity	$r = 0.42$	
		RM – transverse modulus of elasticity	$r = 0.41$	
		RM – longitudinal compressive strength	$r = 0.64$	
		RM – transverse compressive strength	$r = 0.48$	
Acuña et al. [32]	Scots pine (*Pinus sylvestris* L.)	*RM* – density	$r^2 > 0.80$	
	Black pine (*Pinus nigra* Arlond.)			
	Maritime pine (*Pinus pinaster* Ait.)			
	Chestnut (*Castanea sativa* Mill.)			
	Walnut (*Juglans regia* L.)			
	Oak (*Quercus robur* L.)			
Faggiano et al. [33]	Chestnut (*Castanea sativa* Mill.)	*RM* – density	$r^2 = 0.51–0.55$	
		RM – bending strength	$r^2 = 0.42–0.53$	
Calderoni et al. [34]	Chestnut (*Castanea sativa* Mill.)	*RM* – longitudinal compressive strength	$r^2 = 0.58$	
Morales-Conde et al. [39]	Pine	*RM* – density	$r^2 = 0.70$	
Piazza and Riggio [42]	Chestnut (*Castanea sativa* Mill.)	*RM* – density	$r^2 = 0.004$	

ronmental conditions are favourable for a specific species, the growth ring is wider). Comparisons of similarities in tree ring sequences in analysed samples coming from a single population made it possible to determine the sequence of wider and narrower tree rings – in other words identifying a common growth pattern. By placing together samples, starting with the oldest ones, dendrochronologists have worked out dendrochronological scales which provide a reference for specific geographical regions and tree species. The age of a sample coming from a tree of unknown date can be determined by matching its growth ring pattern to the pattern of a dated sample [58].

Application of dendrochronological methods requires that the timber fulfils a series of conditions. Among other conditions, it is essential that the sample to be dated includes anatomically distinct growth rings and comes from trees growing across a wide geographical range. The wood of the tree species should also have been used over a long period of time. Oak is an example of a species amenable to dendrochronological testing and fulfils all the necessary conditions [59].

Dendrochronological research is used to determine the age of historical buildings, for identifying different building phases of the structure under investigation and also for uncovering past renovation, repairs and conservation interventions. Aside from extracting cores from wood incrementally [60,61], drilling resistance can be used to generate a representation of annual growth rings, which enables determination of the age of the timber being tested [16,62,63]. There are also now many new techniques for measuring structural, physical and chemical properties of wood at a high radial resolution, including SliviScan™, X-ray densitometry, infrared spectroscopy, computerised tomography, optical and sonic scanning [64,65].

Fig. 3. Resistance drilling device during timber column testing. Drill shape and dimensions (mm) are shown in lower right corner.

Mobile devices for measuring drilling resistance are also effective in assessing tree health and technical condition [66,67]. They allow assessment of the internal tree structure, enabling localisation and determination of the extent of flaws threatening its stabil-

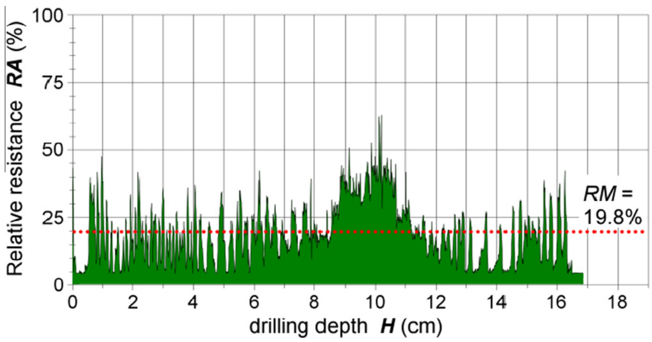

Fig. 4. Example of a drilling resistance graph with marked *RM* value.

ity, such as rot, cracks, mechanical damage etc. and estimating tree density [68]. Static tree measurements provide a means for anticipating threats and counteracting the possible impacts of damaged tree cross-section fragments.

5. Field testing

5.1. Materials and methods

Drilling resistance methods were used to test in-situ the condition of structural timber elements. Testing of drilling resistance of timber elements in floors, roofs and walls were carried out using an IML RESI F-400S drilling device with a drill bit of approx. 380 mm (Fig. 3). The resistance drilling device enabled measurements to be recorded at every 0.1 mm. To calculate the Resistance Measure (*RM*) value – Eq. (1), it was assumed that the entry and exit zone was 3 mm deep, which had not been taken into account in calculations. An example graph showing *RM* values is presented in Fig. 4.

Testing of solid timber was carried out both in heritage buildings of very high historical value and in new buildings with structural elements made from glued laminated timber. A short description of the buildings, in which testing was carried out is presented below (see Fig. 5).

(1) Leopoldinum Auditorium in Wroclaw University, Poland. The largest room in this baroque Wrocław University building was built between1728 and 1732. This is one of the most important heritage buildings from the baroque period in Silesia (Poland). The whole ceiling surface is covered with an elaborate baroque painting [69].
(2) Main Railway Station in Wroclaw, Poland. The building was built in an English neo-gothic style in the years 1855–1857. The architect responsible for what was once the largest building of its kind in Europe was the German architect-Wilhelm Grapow [70].
(3) The St. Mary's Assumption Church in Leszno, Poland. The church was built in the years 1795–1796 based on a timber frame to serve the protestant community. In 1868, clay in-fill material was replaced with bricks. In 1946, the building was taken over by the Catholic Church.
(4) Castle in Prószkow, Poland. Construction began in 1563. In 1677, the building was reconstructed after the Swedish army had burned it down in 1644. The tented timber roof that remains today was built in 1823. The castle has four wings with a rectangular courtyard and distinct avant-corps corner pavilions in the form of bastions.
(5) Residential-commercial building near Lwowek Slaski, Poland. The building was built most probably at the turn of the 19th century and has been adapted for residential use. The building has no basement consisting of a ground and first floor and a usable attic with a rectangular floor plan measuring 9.0 × 19.3 m. The brick walls of the ground floor are covered in stone (surface layer) and made with ceramic bricks, whereas the timber walls of the first floor are supported by posts and bolts.
(6) Klekotki SPA, Poland. In 2008, this timber barn with a floor plan of 12 × 25 m in Klekotki was reconstructed using elements from a demolished barn in another location. Following construction of the timber barn, eight internal 'cubicles' were laid out using short steel posts and beams. The steel 'cubicles' were covered with concrete ceilings, which were linked together by stairs and footbridges. A biological regeneration wellness SPA was located in this reconstructed barn.
(7) A residential building based on a corner-timber frame structure in Bogatynia, Poland. The building was built towards the end of the 18th century and its corner-timber frame structure is typical of regional architecture of the Izerski Uplands region. The walls on the first floor and gable are made of a wattle and daub construction with clay in-fill, the ground floor walls are made from timber logs, external wooden posts support the first floor with brick wall fragments. Timber roof and ceiling structures.
(8) Brzeg Town Hall, Poland. The building was built between 1569 and 1577, following a fire which destroyed the original 14th century Town Hall. Currently one of the most valuable renaissance heritage buildings in Poland. The Town Hall is still the seat of the municipal authorities.
(9) The Church of St. John of Nepomuk in Wrocław, Poland. The building dates back to the turn of the 16th century. The church structure was built originally in the village of Stare Koźle. At the end of the 18th century, the church was dismantled and moved to Kędzierzyn. In 1913, the church was disassembled once more and re-assembled in its new and current location in the Szczytnicki Park in Wrocław, where it is part of the Centenary Exhibition [71].
(10) Central Railway Station in Stockholm, Sweden. This is the largest train station in Sweden and Scandinavia, which was built in the years 1867–1871. A part of the building complex is currently under renovation. The interior load-bearing walls and floors of the building are a timber construction made from solid timber.
(11) Skansen Lejonet, Gothenburg, Sweden. Skansen Lejonet was built in the years 1687–1693 and is one of the few remaining locations, where traces can be found of the original defence structures with walls up to 4 m thick, which made Gothenburg one of the most heavily fortified towns in Sweden at that time. The timber beams were made from large diameter pine logs. Today, the building as a whole and more specifically the wooden-floor rooms are used for weddings and dinners [41].
(12) Nationalmuseum in Stockholm, Sweden. Built between 1844 and 1866, the structure was inspired by North Italian Renaissance architecture. The building is the seat of the Swedish National Art Gallery.
(13) Sports hall in Byczyna, Poland. The building was completed in 2001 and is part of a middle school. The sports hall is a single-story building, which includes a full-size handball field. The load-bearing structure of the hall was built using frames made from glued laminated wood. Due to numerous cracks in ridge and corner nodes, the building is currently not in use.
(14) Tennis hall in Wroclaw, Poland. The building was completed in 2002. The hall has a floor plan of approx. 40 m × 55 m and includes 3 tennis courts. The load-bearing structure of the hall roof is comprised of girders made of glued laminated hockey type timber.

Fig. 5. Buildings for which drilling resistance tests have been carried out (numbered in accordance with descriptions in the text and in Table 3).

(15) Main Library of Wrocław University, Poland. The building was built in the period 2003–11 with one floor beneath ground level and seven floors above ground level. The surface area of the building as a whole is more than 46,000 m^2, whereas the space inside exceeds 179,000 m^3. Part of the roof construction comprises trellis roof trusses made from glued laminated wood. The glued laminated wood has been used also for part of the large-scale window frames.

5.2. Results and discussion

The results of testing the condition of wood in ceiling, walls and roof structures are presented in Table 3.

The tests, which were carried out in the timber elements of the buildings listed above, were first and foremost qualitative in character. The goal was to describe the condition of material and the extent of damage. The change co-efficient obtained for *RM* values exceeds 50% in some instances (position 10, 11, 12 in Table 3),

Table 3
Summary of average resistance for investigated structures.

No.	Building	Construction date	Testing focus	Tree species	No. measurements	Resistance measure *RM* (%)			
						Mean value	Range	Std dev.	CoV
1	Leopoldinum Auditorium in Wroclaw University	1728–1732	Rafter beams.	Scots pine Pinus sylvestris L	57	29.6	6.6–64.3	10.8	36.5
2	Main Railway Station in Wroclaw	1855–1857	Rafter beams	Scots pine Pinus sylvestris L.	20	32.0	15.9–57.8	11.3	35.3
3	St. Mary Assumption Church in Leszno	1795–1796	Roof structure and timber frame structure for walls	Scots pine Pinus sylvestris L.	20	17.7	6.9–36.7	7.5	42.2
4	Castle in Prószków	1863 (reconstruction)	Construction elements of the tented roof of the northern tower	Scots pine Pinus sylvestris L.	20	22.3	11.3–39.1	8.1	36.3
5	Residential-commercial building near Lwówek Śląski	Turn of 19th and 20th centuries	Structural elements of load-bearing walls for first floor	Scots pine Pinus sylvestris L.	22	26.3	12.5–45.4	10.5	39.8
6	Klekotki SPA	Beginning of 20th century	Structural load-bearing elements of the wall frame	Scots pine Pinus sylvestris L.	20	30.5	23.0–43.2	6.6	21.7
7	Residential building of based on column structure in Bogatyna	End of 18th century	Wall structure of the first floor and roof structure	Scots pine Pinus sylvestris L.	20	29.3	20.8–39.2	5.6	19.3
8	Brzeg Town Hall	1570–1572 (reconstruction)	Roof structure	European larch *Larix deciduas*	25	37.5	23.5–71.2	12.7	33.9
9	Church of St. John Nepomuk in Wrocław	Turn of the 16th and 17th centuries	Log wall construction	European larch *Larix deciduas*	50	29.7	12.7–67.4	12.0	40.5
10	Central Railway Station in Stockholm (Sweden)	1867–1871	Roof rafters on first and second floors	Unidentified softwood	31	16.3	4.2–29.8	7.7	47.1
11	Skansen Lejonet, Gothenburg (Sweden)	1687–1693	Floor beams	Scots pine Pinus sylvestris L.	51	23.0	3.9–57.8	12.7	55.3
12	Nationalmuseum in Stockholm (Sweden)	1844–1866	Roof structure	Unidentified softwood	15	28.2	8.0–63.5	14.9	52.8
13	Sports hall in Byczyna	2001	Columns and supporting beams for frame	Scots pine Pinus sylvestris L. (glulam)	24	27.5	14.2–48.1	11.2	40.8
14	Tennis hall in Wroclaw	2002	Hockey type supporting beams	Norway spruce *Picea abies* (glulam)	20	34.9	25.4–45.4	7.5	21.6
15	Main Library of Wrocław University	2003–2011	Grid roof supporting beams	Norway spruce *Picea abies* (glulam)	20	19.9	11.9–29.8	6.0	30.3

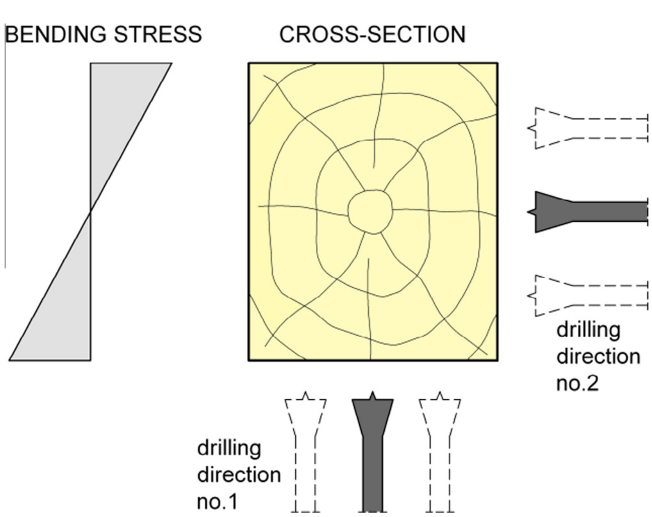

Fig. 6. Examples of possible drilling directions for tested elements subjected to bending.

which puts into question the possibility of correlating *RM* values with the mechanical properties of timber and using this method for estimating those properties. The *RM* values depend on many factors, especially the tree species, wood condition, moisture and drilling direction. Moreover, it is important to remember that tests are carried out in specific points – the result is thus dependent not only on the drilling direction, but also on the location of the drilling point with respect to the height or width of the cross-section. In addition, the influence of strain of the elements tested on the *RM* value is also unknown (Fig. 6).

Fig. 7 presents drilling resistance graphs for three different locations of a drill bit in a single beam cross-section made of glued laminated timber. The focus of the test was a GL 24 h-class timber beam with a transverse cross-section of 140 × 240 mm. The graph clearly shows that the direction of drilling in relation to annual tree ring growth has an influence on the drilling resistance value – the *RM* values for measures No. 2 and 3 are similar (15.0% and 13.8%), whereas for reading No. 1 which involved introducing the drill bit at right angles to the annual tree rings, the value is significantly lower (*RM* = 6.2%). Moreover, variations in the wood structure influence also the *RM* value (knots, possible presence of core).

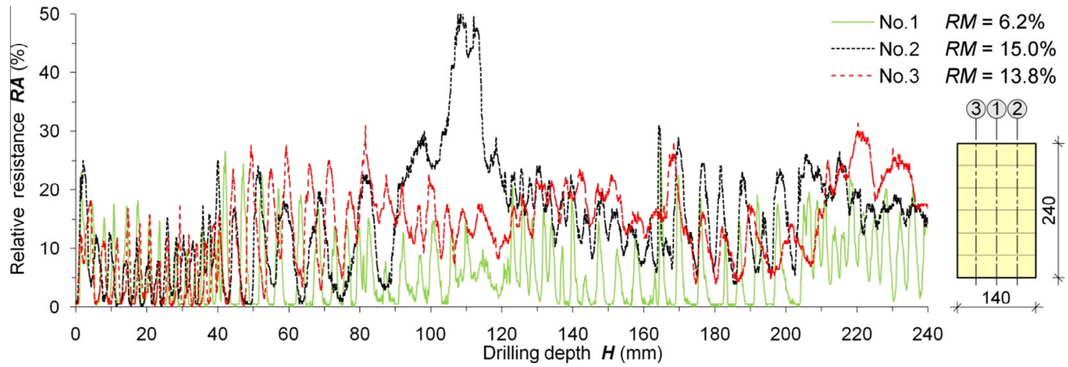

Fig. 7. Drilling resistance graphs for three different drilling sites in a single beam cross-section made of glued laminated timber.

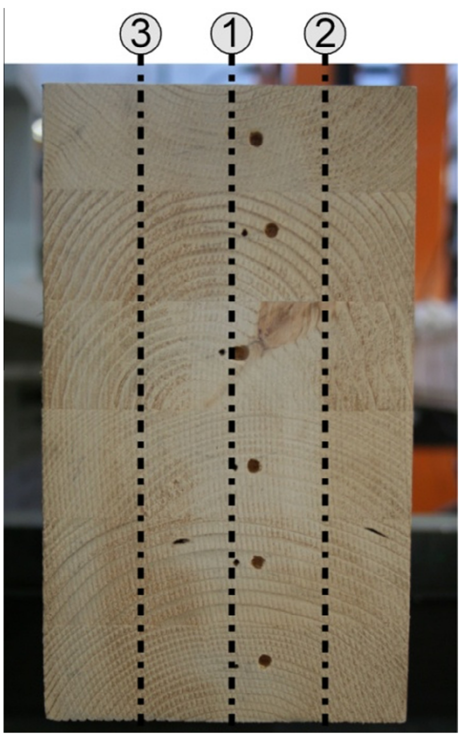

Fig. 8. Cross-section of the tested beam made from glued laminated timber with axes marking out the points where drilling resistance measures were taken (the openings visible result from tests carried out with stress wave and ultrasonic techniques).

For measure No. 2, the graph clearly indicates (Fig. 7), the influence on drilling resistance of the knot located in the third from the top lamination (Fig. 8). The knot has a higher density, but this higher density corresponds to a lower mechanical performance of the member. The drilling can be carried out randomly radially or tangentially to the growth rings. The tangential drilling is generally very uniform, because the differences between early and latewood are attenuated for a simple geometrical reason. In the case of glulam, however, interpretation of resistographic drilling results can be very difficult.

Due to variations (e.g. knots, cores) and anisotropic structures (actual difference in drilling direction in relation to annual tree rings – Fig. 8), the *RM* values differ significantly from each other even in measurements of the same cross-section.

The tests had a point focus and so estimating properties responsibly requires a large number of point measures. The resistance drilling method enables only an initial estimation of the timber properties based on an assessment of the internal defects of the material.

In the in-situ testing described here, the resistance drilling of timber was used to:

- assess the condition of timber in support areas for rafter beams and corner areas in relation to biological damage caused by pests;
- assess the depth of wood damage with the goal of reducing the transverse cross-section – inter alia [53].

6. Conclusions

Based on the review of the literature and own field research, it was possible to formulate the following conclusions:

(1) Using the drilling resistance method in situ allows for: localising flaws and discontinuities internal to the timber elements without affecting their functional properties, assessment of the extent of wood damage in the tested elements, inspection of wood condition covered by other materials (plaster, gypsum covers, brick walls etc.) without disassembly.
(2) Change co-efficients obtained in field conditions for the *RM* value exceeded in places 55% (Table 2) putting into question the possibility of correlating *RM* values with timber properties and using this method for assessment of those properties. For this reason, the method should be treated as a qualitative assessment rather than a quantitative one [72].
(3) The resistance drilling method enables quality assessment of timber based on measures of drilling resistance and assessment of internal defects of the material e.g. in accordance with the categorisation proposed in [48]: excellent/knot; sound; sound-to-medium, medium, medium-to-decayed; decayed; very decayed, void/fracture.
(4) Testing has a point focus and so making responsible estimates of timber properties requires many measurements. The laboratory testing carried out by the authors on bending elements made from glued laminated timber sourced from carefully selected wood (machine sorting in relation to strength properties) confirm the proposition that it is difficult to find a close correlation between *RM* values and flexural strength and modulus of elasticity.
(5) The drilling resistance graph is influenced by many factors, including inter alia wood moisture, drill bit sharpness and angle and direction of drilling.
(6) The *RM* value is influenced also by defects appearing in the timber: knots (very high resistance to drilling) and damage zones (zero or close to zero resistance to drilling), which should also be taken into account in analysis.

(7) The influence of the strain of timber elements on resistance drilling values is unknown and requires a dedicated research programme, which will take into account the variability of different structure elements (ceiling, wall and roof elements) and ensure that tests control for direction of drilling and moisture of the cross-sections, in which measurements are carried out.
(8) The results obtained using the Resistance drilling method can be used for assessing the depth of wood damage with a view to reducing the cross sections of structural elements [53].
(9) Although many methods provide for non-destructive assessment of physical and mechanical properties of old wood in timber structures (Table 1), no single method can provide a complete data set. Thus, it is recommended that a combination of NDT methods be used in assessment of a building, along with visual strength grading [73].

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