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In-situ compression stress-deformation measurements along the timber depth profile

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Abstract. The paper presents a novel concept and a prototype of a diagnostic tool for in-situ assessment of timber in existing structures and buildings. The device enables direct determination of conventional compressive strength and modulus of deformation in arbitrary depth along timber profile. The measurement of the stress-deformation relationship is performed in a prepared hole of a very small diameter by means of a special small size symmetrical loading jack. Testing and verification of the new device behaviour during loading of wood along the fibres has been carried out on fir which is the most frequent wood species in European buildings. The comparison of stress-strain diagrams acquired by means of the new device with those measured in compliance with the European standard for testing of wood shows a very good correlation including the determination of the compressive strength values. This semi-destructive method causes a very gentle damage and can be also used for the assessment of historic timber structures.

Introduction

A number of up-to-date in-situ diagnostic devices and methods use drilling for the description of behaviour and properties of a material. Gently destructive methods (usually denoted as MDT, i.e. moderately destructive techniques) are significant for the practice; they provide directly measured mechanical characteristics. The best known of these methods as regards wood is resistance microdrilling, in which the energy consumed by a thin borer with 1.5-3.00 mm in diameter penetrating the timber is measured and the measured resistance and the borer position can be recorded digitally to a computer memory media; concurrent graphical output in the form of a print of paper tape is also possible [1]. The maximum values of the measured resistance in the graphical record correspond to a higher wood density, while the minimum values are related to a lower relative resistance of wood. The differing drilling resistance can also reveal different levels of damage [2]. Analogical devices are produced for the testing of inorganic materials, especially stone and mortar. Another alternative for the description of behaviour and properties of wood is a mechanical measuring device that measures fracture strength and compressive strength in bending along the fibres of radial cores [3]. The corresponding parameters are gained from the radial core (5 mm in diameter), which is taken from a wooden element. The typical strength of wood is dependent on the direction of loading with respect to the direction of fibres in its structure; therefore, when loading samples in a testing device, it is necessary to pay attention to its correct orientation. The mechanical controls of the device consist of 4 different levers and it is usable for the field research. The radial core, taken by an increment borer or another specially modified borer, is broken or pressed in the device, while the consumed energy is measured. The values gained by this measuring are compared with the corresponding data for the particular wood species in tables that are included in the device accessories. The extracted radial cores can also be loaded in a laboratory by a grooved jaw, which enables loading by compression perpendicular to the core axis, i.e. in compression along the fibres [4, 5]. The radial cores can thus be used for determination of several wood properties, such as density, moisture content, modulus of elasticity and compressive strength along the fibres. Until recently, the range of NDT (non-destructive technique) and MDT methods missed a solution enabling measuring of mechanical properties at various depths of an investigated wooden constructional element.

The presented paper introduces a newly designed device based on the measurement of conventional strength and the modulus of deformation of wood in a drilled hole; the measurements are taken using a small size loading jack. This paper also presents results of measuring performed with the purpose of verifying the device functionality. The aim of the development was a design of a device that would enable to determine the conventional strength and the modulus of deformation in compression along the fibres directly in the field, which was a method still unavailable. Another advantage is the possible establishment of the mentioned properties gradually, along the entire cross-section of the evaluated element.

Device construction

This new diagnostic device (Fig. 1, 2) is designed to measure mechanical properties of wood using non-destructive or slightly destructive investigation of its behaviour when loaded by a small size jack inserted in a pre-drilled hole. The device can be used both in a laboratory and in the field to determine the condition and quality of timber. By its application, the dependence of deformation on the tension brought about by pressing symmetrically placed jaws (stones) apart in a pre-drilled radial hole with 12 mm in diameter.

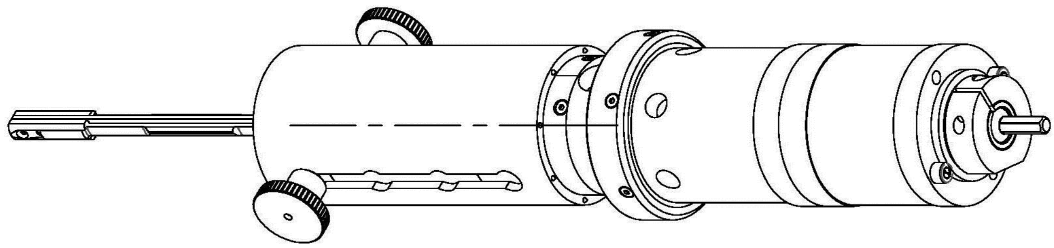

Fig. 1 – Axonometric projection of the newly designed device

The construction of the device consists of an adjustable shell with arresting screws, battery cover and cover of electric installations secured by screws, which are fixed to the device's body in the longitudinal direction. In the top part of the device body there is the mechanism consisting of a drawbar screw secured against turning by a bolt, a drawbar nut with a bearing, and nut socket secured by screws. The drawbar screw has a load gauge screwed on in its conical bottom part; the drawbar is screwed to the load gauge; the drawbar allows for movement to the sides thanks to its joint and the joint pin. The bottom of the drawbar is connected to push-apart wedges by a wedge screw and wedge pins. The jaws with flexible arms are fixed by a jaw screw to the device's body. The flexible arms allow for the movement of the jaws when being pushed apart by the wedges and they keep a constant distance from the device body. The displacement sensor is fixed to the device body in its upper part. It consists of two metal plates with tensometric measurement of bending deformation caused by the conical part of the drawbar screw, which is in proportion to the axial shifting and thus also the distance to which the jaws are pushed apart. Inside the device, there is a transmitter electronically connected to the displacement sensor and the load gauge. The transmitter also has a wireless connection to a computer. The device is driven by a cordless drill with a gearing.

The advantage of the device is the possible gradual recording of the force and shift of jaws (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 provided by two grooved screws, for positions (core depths) 5–25, 35–55, 65–85, 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 jaws are pushed apart by the drawbar with the push-apart wedge (Fig. 3) into the walls of the hole. The maximum depth of possible loading on both sides is 1.5 mm. The drawbar drive is provided through the screw with a nut (or a rack and pinion, or a hydraulic circuit). The source of power is a cordless drill with an epicyclic gearing, but also a manual power can be used by means of a one-hand crank. The rounded jaws are 5 mm wide and 20 mm long. The jaws are manufactured from a special tool steel. The jaws 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 jaws it is sufficient to release the push-apart force.

Fig. 2 – The overall view of the newly designed device

Fig. 3 – The detail of the drawbar with the wedge and rounded jaws

The force of the drawbar drawing is continually recorded. It is calibrated to the real force of the loading jack and simultaneously related to the measured distance of movement of the jaws (Fig. 4). The force is measured by means of the load gauge inserted between the upper edge of the drawbar with the joint and the drawbar screw. The displacement is measured by two plates with tensometric measuring of the bending deformation brought about by the conical part of the drawbar screw, which is in proportion to the axial movement and also the distance to which the jaws are pushed apart. The signals are wireless transmitted to a portable computer where they are processed.

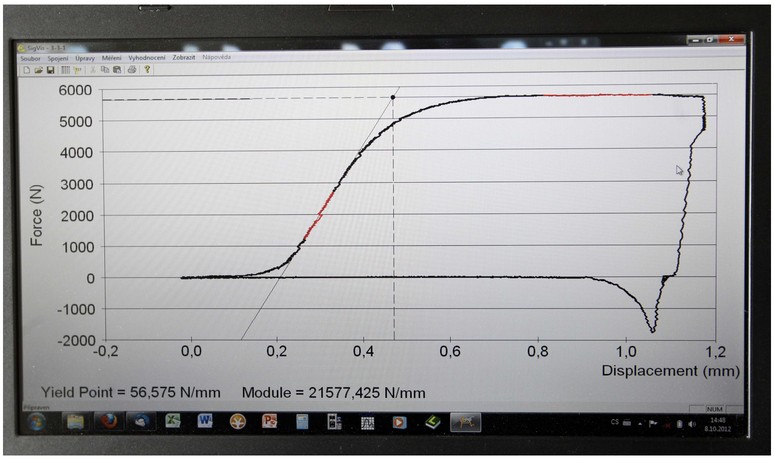

Fig. 4 – Record of the force for the loading jack related to the measured distance of movement (displacement) of the jaws

Experiment

Historical wooden constructions in the Czech Republic often contain fir wood; therefore, we chose the wood of Silver Fir (*Abies alba Mill.)* for the verification experiment. To verify the functionality of the new device, especially as regards mechanical properties of timber, measuring was conducted on four beams 1 to 2 m long. The sections of the beams came from tie beams of the truss of the St. Mary's Church in Vranov nad Dyjí (Fig. 5). Based on dendrochronological assessment, the trees were felled in years 1696–97 [6]. The used parts of the tie beams were taken during the truss reconstruction. Besides the damaged ends of beams, about 1 cm of undamaged beams were cut off so that wooden plated joints could be implemented (Fig. 6).

Fig. 5 – The overall view of the church in Vranov nad Dyjí, the timber for experiments was taken from its truss

Fig. 6 – The place where the tie beam endings used for the verification experiment were extracted

Fig. 7 – Longitudinal sections cut in the place of drilling with marks of screws and measuring points of the new MDT method, beams 2, 3, 4, 5 (in the ascending order)

All four beams (cross profile of 200x240 mm) were drilled by means of a milling bit with 12 mm in diameter, always in purely radial direction, in 100 mm distances (Fig. 7). The depth of the drilled hole on one side of the beam was 130 mm, which enabled us to perform measuring in four layers: layer 1 (5–25 mm), layer 2 (35–55 mm), layer 3 (65–85 mm), and layer 4 (95–115 mm). The depth of the hole on the other side was about 60 mm and the measuring was performed in one layer only (5–25 mm) – layer 5.

The positions of measuring are marked by two vertical lines and a number in Fig. 7. In total, five measurements were performed for one drilled hole across the entire profile. The measuring was also conducted at the place of the decayed beam end but the results were not taken into account due to the very low measured values. The results of measuring of beam 2 were evaluated for holes 8–12 (25 measurements), in beam 3 holes 1–9 were evaluated (45 measurements), beam 4 holes 1–7 (35 measurements), beam 5 holes 6–12 (30 measurements), represented by longitudinal sections at the place of drilling with marked positions of measurements (Fig. 7). In total, the new device measured 140 positions, out of which measuring in 5 positions was damaged and therefore excluded.

After a gradual drying of the beams they were conditioned to a moisture content of 12% and then the actual measuring was conducted: the measuring part was inserted in the radial hole and the device was laid on the tested element using the cylindrical shell. The jaws were pushed apart along the fibres while the drawbar was drawn out with the push-apart wedge on which the jaws moved. The drawbar operation was driven through a bolt with nut and a cordless drill with epicylic gearing. The prints of the jaws in the timber are obvious in Fig. 8, which also shows the distances between the individual layers of measurement across the element.

Fig. 8 – A detail of a drilled hole cut up, with visible prints of the jaws

Mechanical properties were determined using the record of the measured data in the form of a stress-strain diagram with the record of the force used for the drawbar that was calibrated to the real force of the loading jack and related to the measured distance of the jaws movement (displacement) (Fig. 4). Axis x represents the depth to which the jaws are pushed, axis y shows the force necessary for the jaws to be pushed into the walls of the drilled hole. F_{max} (in Fig. 4 - Yield point) was established from the intersection of tangents of elastic and plastic parts of the stress-strain diagram. Conventional compressive strength CS_C was determined from the proportion of the ultimate load and the area of jaws. The modulus of elasticity cannot be calculated directly from the diagram; the modulus of deformation was established using the angle of the force and deformation.

To verify the functionality of the new device, we compared the quantities measured by the new device with the values gained by the testing of standard samples by destructive tests in compliance with ČSN EN using the Zwick Z050 universal testing device and the stipulated procedure of the test. The results were evaluated by the TestXpert application. Two standard samples, with dimensions 20x20x30 mm corresponding to ČSN EN, were cut in the places adjacent to each of the measurement points. Compressive strength along fibres was determined using the samples in compliance with the standard and then correlated with the results of measuring by the new device.

Test results

The regression equations, including the coefficient of determination R^2, describing the relation between strength S_C and strength CS_C, are presented in Fig. 9. The values of R^2 indicate quite close dependences. Similar dependences are found when another MDT device based on pin penetration is used [7] or when radial cores extracted by means of hollow borers are tested [8]. The pilot tests conducted using timber from a historical construction of a truss proved that the new MDT method is sufficiently sensitive to natural changes of properties (distribution along the element profile). It is necessary to mention that the natural variability of the material was strengthened by the presence of defects (knots and cracks) in the tested elements, which together with the limited number of possible repetitions impedes a possible finding of an even closer relation like we find in defectless samples. The conventional strength of wood determined by the new device would naturally correlate better with strength in concentrated compression along the fibres.

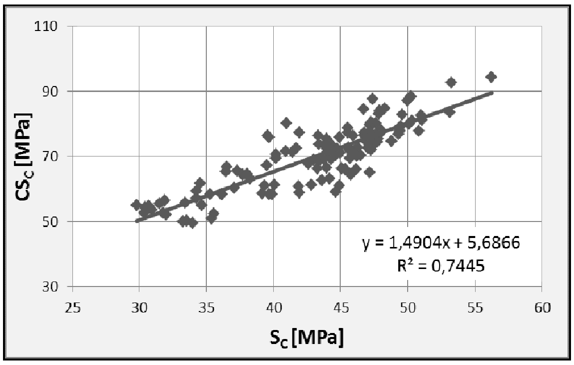

Fig. 9 – Dependence of S_C and CS_C in particular places of measuring by the newly designed device

Wood properties from the particular places of measuring by the new device as well as mechanical properties established by compression tests in compliance with the standard, changed in dependence on natural changes of properties (Fig. 10), which especially concerns the distribution along the width and slightly also along the length. Individual layers of measuring along the width are marked by numbers 1–5 and also distinguished by the colour of the lines linking individual measurements in different holes within one layer (depth of measuring within a hole) (Fig. 10).

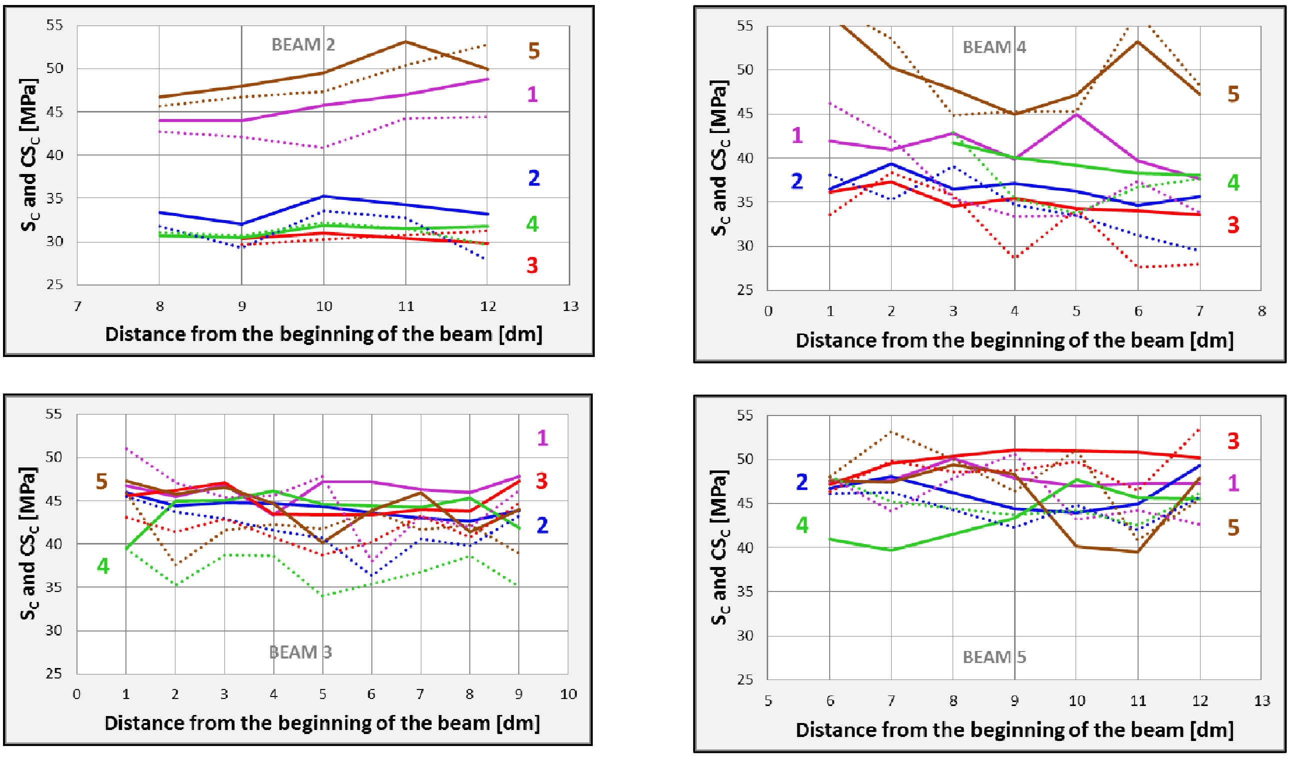

Fig. 10 – Progress of S_C (full line) and CS_C (dotted line) for particular holes and layers of measuring in beams 2, 3, 4, 5

Measuring was conducted in four layers from one side: layer 1 (5–25 mm), layer 2 (35–55 mm), layer 3 (65–85 mm), layer 4 (95–115 mm); and only one layer at a depth of 5–25 mm from the other side: layer 5.

S_C measured in standard compression tests (full lines in Fig. 10, 11), as well as CS_C measured by the new device (dotted lines in Fig. 10, 11) confirm a considerable difference in the distribution of the explored properties in the case of beams 2 and 4, where the surface layers reached a strength of 45–50 MPa and the middle layers around 30–35 MPa. Slight differences in distribution of properties were found in the case of beams 3 and 5, the higher density in the surface was not as marked as in the case of beams 2 and 4. CS_C as presented in the graphs (Fig. 10) has been derived using the correlation model (Fig. 9), which allowed us to compare the values of CS_C and S_C for the individual places of measuring, which are highly similar. The same conclusions are valid for graph Fig. 11, where the values of S_C and CS_C are averaged based on the particular layers of measuring.

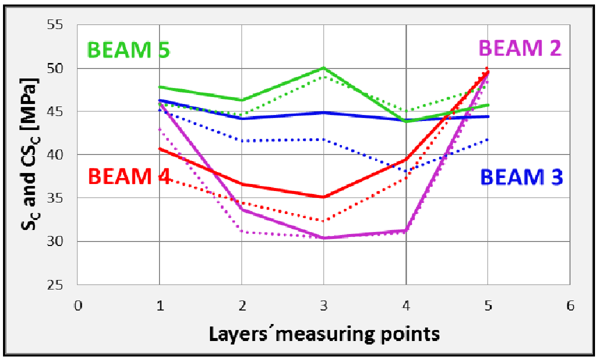

Fig. 11 – Average values of S_C (full line) and CS_C (dotted line) for particular layers of measuring in beams 2, 3, 4, 5

Summary

The primary aim of this paper was to present a gently destructive diagnostic tool of new construction, usable both in the laboratory and in the field for the establishment of mechanical properties of timber. The basis of the device is the measurement of conventional strength and the modulus of deformation when loaded by a symmetrical jack in a pre-drilled radial hole with a diameter of 12 mm.

The secondary aim was to verify the device functionality using the wood of Silver Fir (*Abies alba Mill.)* within the common variability of properties. The material for the experiment was parts of beams extracted during a reconstruction of a historical truss of the St. Mary's Church in Vranov nad Dyjí. We can conclude that the device is usable within the broad scale of natural properties of fir wood. The basic utilization of the new device in the range of properties of softwoods used in historical trusses in the Czech Republic has been verified. This research has also proved that the device is sufficiently sensitive to natural difference and changes of properties (e.g. distribution along the width and presence of defects). For this reason, further studies should experiment with sets with a lower variability and a higher number of repetitions (e.g. sound wood of spruce with a closer range of densities, etc.).

Based on measuring at 135 positions, we monitored relations between quantities measured by the new device and wood properties established by standard tests. Strong relations were mainly found between wood strength and conventional wood strength determined by the loading jack. This was described in more detail by a simple model. The conventional strength of wood correlates with the other examined parameters of wood and the future possible experiments could further focus on other practically usable relations.

The entire progress of the stress-strain diagram and the established values of the conventional compressive strength along the fibres correspond to sound wood of fir. A lower quality of timber caused by e.g. wood-destroying factors (decay) will be manifested in a decrease in the measured force to the relative deformation. The device enables a researcher to measure in various depths of the drilled hole and it is possible to determine in what part of the cross profile of the assessed element the decrease in mechanical properties occurs. Conditions for a proper use of the method are drilling of the hole across the fibres in the radial direction, where earlywood and latewood alternate; and orienting the measuring probe along the fibres and, in constructional elements, also parallel with the element axis.

The device construction is light and thanks to its independence of the power supply it can be well used in the field. In contrast to other methods, the new device allows for a very precise establishment of mechanical properties in the depth profile of the assessed element. A disadvantage is the necessity to drill a hole with 12 mm in diameter. Like other field methods used for the diagnostics of integrated timber, the presented method for measuring conventional strength of wood shows a significant dependence on the content of water in the explored material. This dependence is well-known and there are suitable relations available for its correction.

Acknowledgments

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