Derivation of Mechanical Properties by Pushing of a Pin into Wood

Jan Tippner[1], Michal Kloiber[2], Jaroslav Hrivnák[3]

Abstract During the structural/technical surveys of built-in wood in historical structures, the priority is to maintain the maximum proportion of the original material. This requires a reliable determination of the extent of damage while also determining the mechanical properties of wood which serves as the basis for the static calculation of the whole of the structure. The paper presents a new diagnostic tool for *"in-situ"* assessment of timber based on the principle of mechanical resistance against tool (pin) penetration into wood. To verify the proper function of the tool, measuring was conducted using three basic species of softwood. With the aim to discern the variability of properties caused by their distribution along the diameter and the length of trunk, always one complete trunk of spruce, fir and pine was used. The results show a very good correlation of the average force necessary for pin pushing into wood with the wood density and strength ascertained using standard specimens in compression parallel to the grain.

Keywords pushing, pin, resistance, mean force, density

1. INTRODUCTION

A number of current diagnostic tools and methods use the measurement of resistance against tool penetration into wood mass to describe behavior and properties of wood (Pellerin and Ross 2002). The most widespread resistance method is measuring the depth of pin penetration in which the pin is shot into the material by a constant energy of a spring (indentor) – this can be considered a semi-destructive method (Drdácký et al. 2006). However, the maximum depth of pin indentation is limited due to the construction of the device and thus only superficial properties are measured (Görlacher 1987; Kasal and Anthony 2004). Another alternative of measuring the mechanical resistance of wood is a penetration test based on repeated pin hammering into wood by means of a hammer with a constant energy (Ronca and Gubana 1997).

Moreover, there are other resistance methods for wood diagnostics, e.g. resistance microdrilling (Kasal and Antony, 2004) or the screw-withdrawal resistance method (Divós et al. 2011). Instrumented microdrilling differs from the dynamic penetration mainly by the fact that thanks to the gradual penetration through the material we gain an overview of its internal structure. The output is a profile of energy consumption, or a relative resistance, including the elimination of energy consumption caused

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[1] Jan Tippner, Faculty of Forestry and Wood Technology, Mendel University in Brno, Department of Wood Science, Brno, Czech Republic, tippner@mendelu.cz

[2] Michal Kloiber, Institute of Theoretical and Applied Mechanics, Academy of Sciences of Czech Republic, v. v. i., Centre of Excellence ARCchip Telč, Czech Republic, kloiber@itam.cas.cz

[3] Jaroslav Hrivnák, Faculty of Wood Sciences and Technology, Technical University in Zvolen, Department of Mechanical Wood Technology, Zvolen, Slovak Republic, xhrivnak@ is.tuzvo.sk

by friction in deeper layers. The peaks in the graphical record correspond to higher resistance or wood density, whereas lower points are related to a lower relative wood resistance. The screw-withdrawal test uses a simple manual tool for withdrawing a standard screw with 4 mm in diameter driven into a depth of 18 mm (Divós et al. 2011). The outputs of screw-withdrawal methods (e.g. screw withdrawal resistance) are used for indirect establishment of wood density.

The spectrum of the used methods and tools still lacked a solution which would enable a continuous record of resistance against gradual tool penetration into a material to depths corresponding to common dimensions of wooden constructional elements. Now, there is an alternative to timber mechanical resistance measurement and this is a semi-destructive penetration test based on continuous monitoring and recording of a force applied to a gradual pin pushing into a material in relation to the measured distance of pin displacement (Kloiber et al. 2011). The device used for this test is autonomous and portable, yet it is able to ascertain properties in the entire cross section of a wooden element thanks to the sufficient depth of pin penetration; moreover, in contrast to e.g. resistance microdrilling, it retains the character of an indentation test. The output of measuring is a graph of the development of the force applied to pin pushing. The quantities derived from the graph can be used to establish the mechanical resistance of the material.

2. DEVICE CONSTRUCTION

The device (Fig. 1) consists of the movable part of the body, to which a tool base is connected perpendicularly in its lower part and a gear casing in the upper part. The toothed rack is connected to a 5 kN load cell, the load cell connects to a pin indentor, which is mostly of 2.5 mm in diameter and 120 mm in length and is fabricated from spring steel. The pin indentor has a semi-round tip. Parallel to the direction of the toothed rack movement there is a movable pin guideway connected to the body movable part. The pin indentor passes through the tool base in bronze grommets which reduce friction of the pin movement. They are fixed in the tool base by a thin nut (Fig. 2). The device is equipped with a displacement sensor, there is also a wireless connection between the wireless data transmitter and a USB receiver of the recording PC with specially developed software *SigVis* for recording and analysis of measuring.

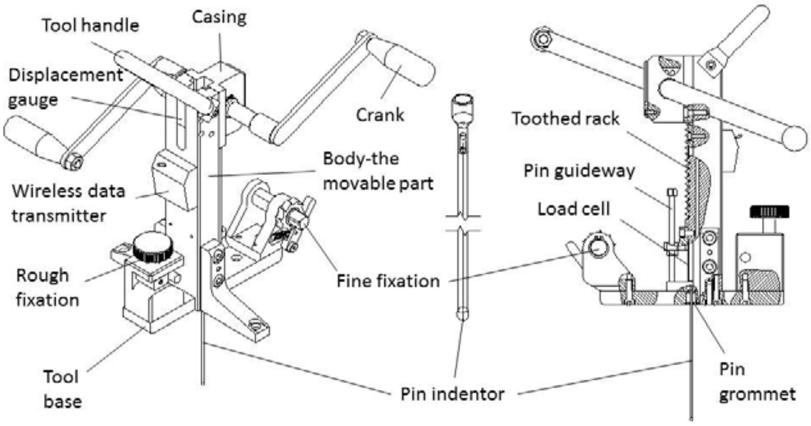

Figure 1 – Axonometric and side view of the device with the pushing pin.

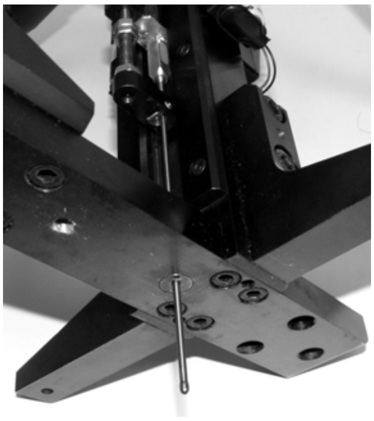

Figure 2 – Detail of pin passage through the tool base.

The body of the device is designed so that it can be fixed to the tested object by means of a fabric strap. The device can also be fixed to the tested element by a roller chain using a similar method. In contrast to the fabric strap fixation, the alternative way is more demanding for manipulation and fixation. Moreover, the fabric strap allows for a more gentle fixation, e.g. if the tested timber is a part of a historic building. Another alternative is fixation by means of mounting screws. This has to be used when the entire circumference of the element is not accessible.

After the device has been fixed to the object, a pin is gradually pushed into the timber perpendicularly to the surface. Its movement is ensured by rack and pinion gear driven by two opposite manual cranks for both hands. The record is assessed in the form of a graph which shows the force measured during the process of pin pushing. The x axis represents the depth to which the pin was pushed; the y axis represents the force needed for pushing (Fig. 10).

Basic parameters are calculated from the record using software *SigVis*, namely work S [N.mm] – as the area under the curve of the diagram, length or the depth of pin penetration L [mm], time of pin movement t [s], the maximum force achieved F_{max} [N] and the minimum force achieved F_{min} [N]. The peaks in the graph correspond to a higher force, i.e. a higher resistance of wood, whereas the lower values of force are related to a lower resistance. Reduced quality of timber caused e.g. by wood-destroying insects is manifested in the graph by a relative drop in the measured force. The measured parameter can be changed by a simple replacement of the indentation pin with a hook for withdrawal of screws or other fixings (Fig. 5). The ability of timber to hold mechanical fixings also depends on its species, density, moisture content and quality. *SigVis* processes the data from the wireless receiver, visualizes them in real time and saves them. It always shows the progress of the force measured at the moment (either in dependence on time x-t, or in mode x-y together with pin displacement), until new measuring is launched in the interface. By this a new data file is created and the application processes a new record (shows a new graph). During measuring, the software evaluates the basic properties, as mentioned above. By dividing work S by the depth of penetration L the mean force F_{AVG} [N] of pin penetration is calculated. This parameter is of key significance for practical assessment of the timber mechanical resistance. Other derived criteria (based on ratios of output quantities) were tested as well; however, these have not found a larger practical significance.

3. EXPERIMENT

During the development of the pin and the device, several measuring experiments were conducted using various wood species and various conditions. The pin with several alternatives of shank and edge was tested separately using a special fixture on the testing device (Kloiber et al. 2009). To verify the proper function of the resulting new device, mainly regarding the variability of wood properties, and thus to verify the range of its usability for the estimation of properties of constructional timber used in trusses in the area of the Czech Republic, we carried out measuring using three basic types of softwood. As we wanted to take notice of the distribution of properties along the diameter and the trunk length, always an entire trunk of a tree was represented – we have chosen Norway spruce (*Picea abies (L.) Karst.)*, silver fir (*Abies alba Mill.)* and Scots pine (*Pinus sylvestris)*. This selection corresponds to the most frequently used material composition of historic trusses in the Czech Republic. The sample trees were carefully chosen from only one closed canopy stand in Zubří in an area called Czech Canada, approximately at 15° E and 48° N at an altitude of 680 m a.s.l. The selected trees were individually felled down, trunks were shortened to 3 m and quarter-sawn so that each of their sides corresponded to their respective cardinal directions as the trunk grew (Fig. 3). The logs were then cut so that only a radial plank from their centre with a thickness of 60 mm was created (Fig. 3). A total of 24 planks for each species were then used for measuring.

After slow drying of the radial planks and conditioning to moisture content of 12 %, the pin penetration test using the new device was conducted (Fig. 4). Pin pushing was carried out in purely radial direction, into a depth of 110 mm, in positions each meter of the plank length, from 1 m to 18 m of the trunk height, for each cardinal direction separately. In total, we had 72 positions for each species of wood. The mean force was established at pushing in a velocity of about 10 mm/s. At the spot adjacent to pin penetration the measuring was also conducted by pin indentor, resistance microdrill and screw-withdrawal method, i.e. variant way of new device usage. Before these semi-destructive tests, also non-destructive measuring by acoustic methods was performed. Complex processing of the resulting vast amount of data will be object of further research; however, the first of the conclusions is e.g. the fact that the output of the new method correlates especially with the outputs of resistance methods. To verify the proper function of the new device, we have used experiments based on comparison of quantities measured during pin pushing and testing of standard specimens by testing machine Zwick Z050 with test control and result evaluation by software TestXpert v 11.02.

Figure 3 – Processing of quarter logs into radial planks of 60 mm.

Figure 4 – Pin pushing with the new device.

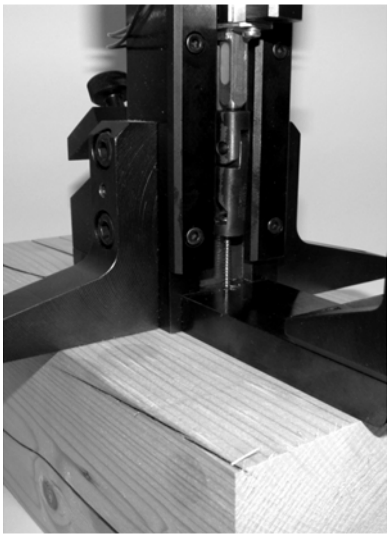

Figure 5 – Screw withdrawal.

The basic compared parameters for device verification were: the height of the position in the trunk (*Tree Height*), wood density (*Density*), wood strength in compression parallel to the grain (MOR_L), proportional limit in the radial direction (PL_R), modulus of elasticity in compression parallel to the grain (MOE_L) and perpendicular to the grain (MOE_R) and also hardness according to Janka in longitudinal (H_L), radial (H_R) and tangential (H_T) directions. The tests were performed in compliance with standard European regulations using 20x20x30 mm (or 50x50x50 mm in the case of hardness tests) samples taken at the individual positions adjacent to the spots of pin pushing. The specimens were closely adjacent so that we could analyze the distribution of properties along trunk radius. The data was further processed in the Statistica 9.0 application (survey analysis of data, verification of distribution normality, independence of elements of the selection, correlation analysis, linear and non-linear regression).

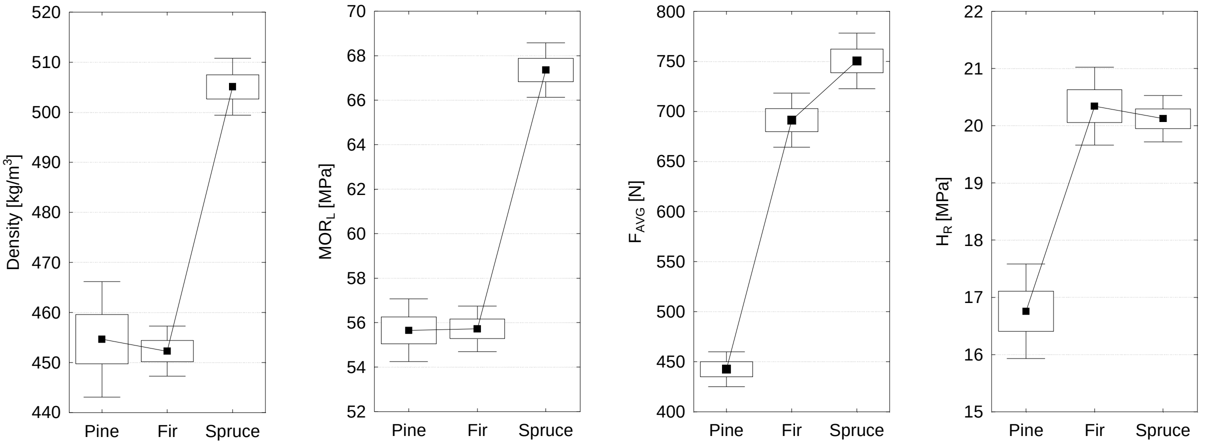

Figure 6 – Boxplots - data for average force (F_{AVG}), hardnesses (H_R), density (ρ) and compressive strength parallel to grain (MOR_L).

Average force, hardness in radial direction, density and strength in compression parallel to the grain of the three wood species are presented in Fig. 6. The results of analyses prove significant difference between the species, in other words, the fact that during the usage of the device it is necessary to respect the tree species from which the tested wood originated. Fig. 6 also shows that the values of the average force for pin pushing into pine wood are disproportionately lower. This phenomenon is caused by the inclusion of soft sapwood in the pin pushing, when nearly a half of the depth of pushing was conducted in the sapwood (by contrast, the average values of density, MOR_L have been established from a larger part of trunk radius containing heartwood). The relatively higher resistance of fir wood corresponds to more complicated working of fir wood (especially when compared with working of pine) and the ability to better hold fixings. The hold fixing corresponds with the ascertained higher proportion of friction during pin pushing and pin withdrawal and mainly the screw withdrawal tests, in which the resistance of fir was about 15 % higher than resistance of sapwood pine.

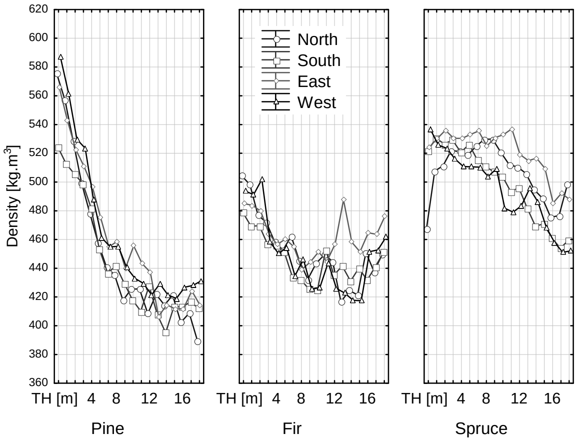

Figure 7 – Distribution of density along trunk and according to cardinal directions.

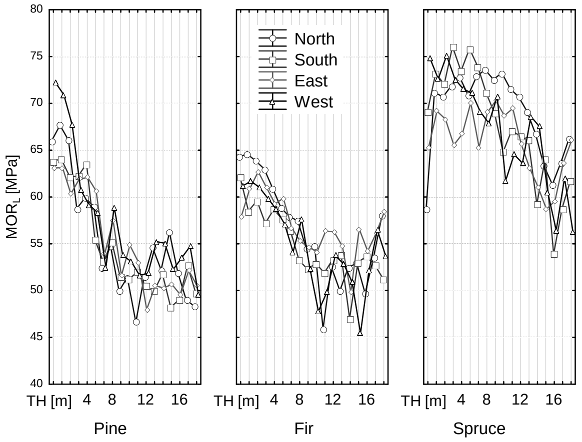

Figure 8 – Distribution of *MOR*$_L$ along trunk and according to cardinal directions.

The distribution of density and *MOR*$_L$ along the trunk and at the same time according to cardinal directions is illustrated in Fig. 7 and Fig. 8. It is obvious that the differences of properties ascertained for individual sides of the trunk are negligible, as was also confirmed by statistical tests (Duncan's test). The distribution perpendicular to the grain needs to be respected for two basic outputs of the measuring by the new device – the record of force and the calculated mean force, each with a different possible usage. The continuous record of the force related to the pin displacement is able to describe the changes in properties along the depth of pin penetration – these changes can be caused by natural distribution of properties, as documented in Fig. 9 in comparison with Fig. 10.

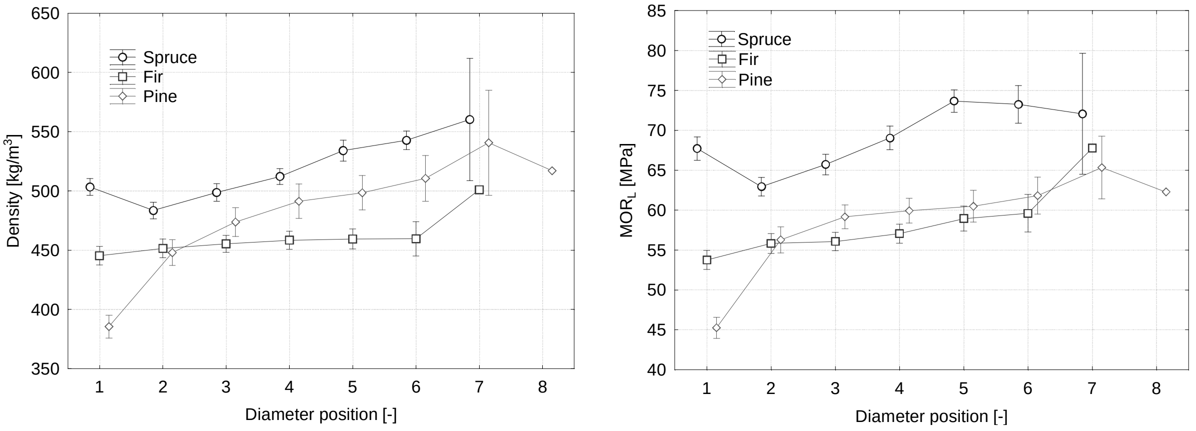

Figure 9 – Distribution of density and *MOR*$_L$ along trunk diameter for individual species (the positions along diameter correspond to positions of samples for the test by compression parallel to the grain).

The x axis in Fig. 9 marks the position of the specimen with a cross section of 20 x 20 mm along the diameter. Position 1 thus corresponds to pin penetration depth 0–20 mm; position 2 (due to the cutting process) corresponds to pin penetration depth 23–43 mm, position 3 - 46–66 mm, etc. When comparing the trend of measured properties in Fig. 9 with the trend of force progress fitted through all graphs for appropriate timber exported from *SigVis* (Fig. 11), we find both the similarity in progress along the diameter and the differences between the three species. The device appropriately reveals the changes of wood properties during pin pushing and it is highly probable that it identifies e.g. wood defects very well; however, if an integral quantity – average force – is used, the significance of property distribution is neglected. Due to the fact that the pin is pushed into a great depth of the trunk, we can neglect the probable effect of distribution along the trunk diameter on the average force (in short, the average force is established from the entire section of pushing).

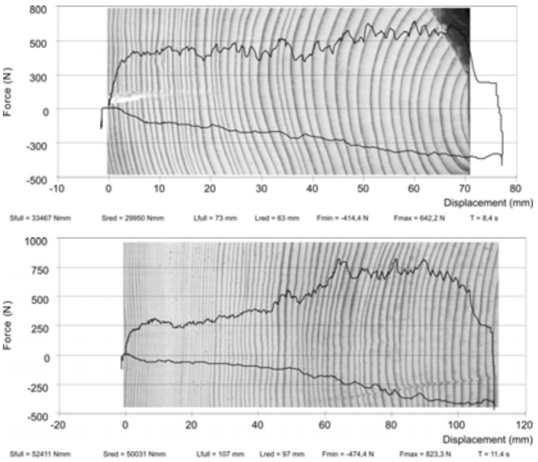

Figure 10 – Record of the progress of force and displacement for spruce wood and for pine wood.

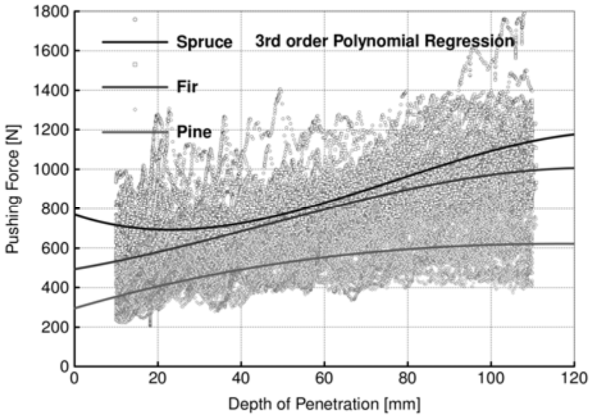

Figure 11 – Trends of force progress during pin pushing into individual species(polynom of 3rd grade fitted through all graphs of wood measurement records).

The differences in properties along trunk were statistically confirmed (strongly e.g. between crown parts and bottom parts) and they can be used to determine the height position of the measured part in the trunk. It is recommendable to respect the effect of the longitudinal distribution and to create alternatives which respect and neglect this effect. Tab. 1 shows the correlation relations between the monitored parameters and the average force. Especially the relation with density and hardness can be considered strong for all species.

Table 1 – Correlations between the indentation force (F_{AVG}) and other estimated variables for three wood species. Bold marked correlations are significant at $p < 0.050$.

	Tree Height	MOR_L	PL_R	MOE_L	MOE_R	***Density***	H_R	H_T	H_L
Spruce	**-0,47**	**0,37**	0,03	0,13	**0,29**	**0,6**	**0,41**	**0,56**	**0,54**
Fir	**-0,37**	**0,41**	0,07	0,11	0,1	**0,65**	**0,58**	**0,52**	**0,4**
Pine	**-0,78**	**0,83**	**0,49**	**0,56**	**0,39**	**0,88**	**0,75**	**0,81**	**0,67**

Due to the significant dependence of average force and other quantities on the height position, it is recommendable to respect this when estimating mechanical properties. The correlation coefficient of all monitored properties (density, strength, hardness, moduli of elasticity) shows an existing dependence; in most cases the Duncan's test confirmed a significant difference of properties along the trunk height. The correlation coefficient of the dependence of the average force F_{AVG} on the height is -0.47 for spruce, -0.87 for pine, and -0.37 for fir. All 3D models are presented in Tab. 2.

Table 2 – Non-linear 3D models deriving density or strength from the average force and height position in the trunk.

z = ***Density*** [kg/m^3], x = F_{AVG} [N], y = ***Tree Height*** [m]		
Spruce	$z=275{,}364+0{,}522305x+3{,}36196y-0{,}00025x^2-0{,}05357y^2-0{,}00618xy$	$R^2=0{,}8256$
Fir	$z=462{,}242+0{,}03533x-12{,}925y+0{,}0000126x^2+0{,}416954y^2+0{,}005628xy$	$R^2=0{,}8265$
Pine	$z=457{,}121+0{,}046248x-7{,}589y+0{,}000282x^2+0{,}418984y^2-0{,}01451xy$	$R^2=0{,}9496$

$z = MOR_L$ [kg/m^3], $x = F_{AVG}$ [N], y = *Tree Height* [m]		
Spruce	z=21,8785+0,101931x+1,6233y-0,000048x^2-0,03134y^2-0,00214xy	R^2=0,6995
Fir	z=52,5924+0,047978x-3,1266y-0,000039x^2+0,092857y^2+0,001288xy	R^2=0,6590
Pine	z=23,5623+0,12592x+0,245726y-0,00008x^2+0,035746y^2-0,0036xy	R^2=0,8285

If the height position of measuring in the trunk is unknown or negligible, we can use the available sufficiently effective relations deriving density and strength from the average force only. Relations between the average force and selected quantities were described more closely by means of linear regression, as is shown in Fig. 12. A summary of the models is shown in Tab. 3, where R^2 also confirm the tight closeness of dependences. In this case, also more complicated non-linear polynomial models were tested; however, their contribution to precision is not considerable. To estimate the moduli of elasticity and proportional limit in radial direction, the relations were not described sufficiently closely by regression. Usually, a closer relationship was found for one species only (often for pine). For the estimate of hardness in all directions, the determination coefficients indicate slightly close relations, which are more significant for hardness measured in the tangential direction. The relations are the least close for the direction of pushing (radial). Although due to the character of wood damage the pin pushing test seems to be the closest to hardness test in the same direction, the damage during pushing is more complicated. Probably, the existence of side pressing during pin penetration, small breaks of ring layers, etc., make the influence of other properties more pronounced.

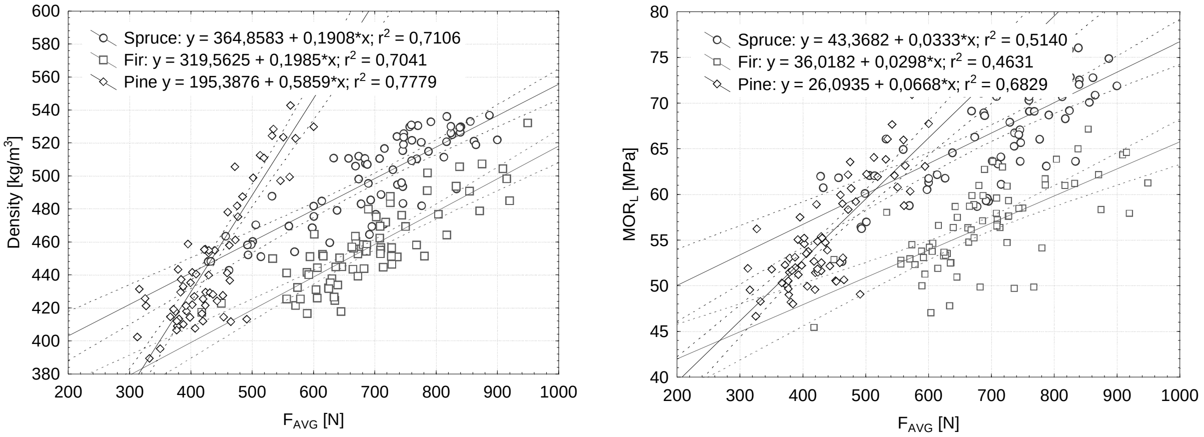

Figure 12 – Dependence of density and average force, dependence MOR_L parallel to the grain and average force.

Table 3 – Linear 2D models deriving density or strength from the average force.

$y = MOR_L$ [MPa], $x = F_{AVG}$ [N]		
Spruce	y=43,3682+0,0333x	R^2=0,5140
Fir	y=36,0182+0,0298x	R^2=0,4631
Pine	y = 26,0935+0,0668x	R^2=0,6829

y = *Density* [kg/m^3], $x = F_{AVG}$ [N]		
Spruce	y=364,8583+0,1908x	R^2=0,7106
Fir	y=319,5625+0,1985x	R^2=0,7041
Pine	y=195,3876+0,5859x	R^2=0,7779

Regression equations, including determination coefficients R^2, which serve for derivation of density or strength MOR_L (z) based on average force F_{AVG} (x) and height position in the trunk (y) are summarized in Tab. 2. R^2 values indicate strong up to very strong closeness of dependences. No close relations were found for the longitudinal and radial modulus of elasticity as well as the proportional limit in the radial direction (R^2 always below 0.5). The explanation is predominantly the high variability of data caused by minor knots – for this reason, R^2 is always slightly higher for pine, where more pronounced knots and thus larger places without their influence are found.

4. CONCLUSIONS

The aim of the study was to test the device using basic softwoods and in common variability of properties – that is why entire trunks were used. We can conclude that the device is usable for a wide range of properties of healthy wood of spruce, pine and fir. The research has also proved that the device is sufficiently sensitive to natural differences among species and to natural changes of properties (distribution along the width and length of trunk, defects). For this reason, it is now appropriate to make experiments with sets with a lower variability and a higher number of repetitions (e.g. healthy spruce wood with a narrower span of density values, etc.).

Based on measuring conducted at 72 positions, the relationships among quantities measured by the newly designed device and wood properties ascertained by standard tests were explored. Strong relations were mainly found among the average force, wood density and strength. These were described more closely by simple models. The average force more or less correlates with other monitored parameters of wood as well and the future experiments could identify and explain other practically usable relations. Moreover, the distribution of properties across the trunk was evaluated, which nicely corresponds to the continuous force record provided by the new method and which is at the same time negligible if an integral output – the average force – is used. The differences in wood properties in the various sides of trunk were not recorded and can thus be neglected for practical usage. By contrast, the distribution along the trunk is significant for the new method and its inclusion as another parameter of the models makes the estimate of wood density and strength more precise. The described differences in properties along the trunk diameter also prove that superficial properties, measured locally by means of current methods, cannot be extrapolated to the entire element, as was confirmed in previous research (Drdácký et al. 2006).

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