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# Variability of spruce (*Picea abies* [L.] Karst.) compression strength with present reaction wood

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**ABSTRACT**: The aim of research was to find out the variability of spruce (*Picea abies* [L.]) Karst.) wood compression strength limits in the direction parallel to grain. The wood strength was examined using samples from a tree with present reaction (compression) wood. The strength was found out for individual stem zones (CW, OW, SWL and SWR). The zone with present compression wood (CW) demonstrated slightly higher values of wood strength limits. The differences in the limits of compression strength parallel to grain in individual zones were not statistically significant. All the data acquired by measuring were used to create 3D models for each zone. The models describe the strength along the radius and along the stem height. The change of strength along the stem radius was statistically highly significant. There was an obvious tendency towards an increase in the strength limit in the first 40 years. With the increased stem height, there is a slight decrease in wood strength.

**Keywords**: strength parallel to grain; spruce; compression wood; reaction wood

As we use wood as a construction material, we have to consider several vital factors to evaluate its quality; and these are not only its physical properties and imperfections, but also its strength properties (wood strength and modules of elasticity). The evaluation of wood is much more complicated than the evaluation of metal because wood is an inhomogeneous anisotropic material. From the practical point of view, wood compression strength parallel to grain is one of the most important wood properties. When a force is applied, deformation occurs. This deformation is manifested as the shortening of the object in the direction of the applied force.

The wood strength parallel to grain, and also the level of the deformation of conifers, depends predominantly on the interconnection of individual tracheids. The strength mainly depends on the S2 layer of the secondary cell wall and the fibril deflection in this layer. The tension is transferred via cellulose macromolecules in the cell walls. Hemicelluloses and lignin fill up the cellulose skeleton and they play a role in the total stability of the cell wall (Požgaj et al. 1997).

The important factors which affect the compression strength are wood density, its species, grain deflection, moisture content, and ambient temperature. The influence of wood density on the strength is positive. Increased density means increased wood strength. The wood species affects the compression strength indirectly through wood density and also through structural parameters, such as the tracheid length, the proportion of lignin and the proportion of late wood. Compression strength of wood parallel to grain decreases with the degree of grain deflection from the longitudinal direction to 90°. Grain deflection by 15° can bring about up to a 20% decrease in the strength. With increasing moisture content (from 0% to the fibre saturation point) compression strength decreases: moisture content being increased by 1%, compression strength decreases

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by 4%. The negative influence of the temperature on wood compression strength parallel to grain is especially obvious after a long-term exposure to higher temperatures (Kollmann 1951; Niemz 1993; Požgaj et al. 1997).

As wood density is highly variable in relation to the position in the stem, also variable strength in the appropriate stem parts can be expected. That is why Palovič and Kamenický (1961) examined the variability of the spruce and fir wood compression strength parallel to grain in dependence on the position in the stem. They found out that the maximum compression strength parallel to grain decreases in the transversal direction from the stem perimeter to its centre and in the longitudinal direction from the stem base to its top. Therefore, the authors conclude that the most suitable properties are localized in the stem perimeter and in its lower third.

The compression strength parallel to grain of compression wood was an object of interest as early as at the end of the 19th century. Nördlinger (1890) was the first to state that spruce compression wood will have the only slightly higher wood compression strength parallel to grain than normal wood. Also, the majority of other authors confirmed the higher compression strength parallel to grain in comparison with the strength of normal wood (Verall 1928; Timell 1986; Požgaj et al. 1997; Gindl 2002; Horáček et al. 2003).

Bernhart (1985) determined the values of strength for various ways of load application, both of samples of normal wood and samples with present compression wood. In contrast to the other authors, Bernhart (1985) found out that the presence of compression wood influences the strength negatively for all examined ways of load application. The compression strength parallel to grain is slightly lower in the samples with present compression wood than in the samples of normal wood.

When fresh wood dries up, even normal wood becomes stronger. The same principle applies to compression wood. When fresh, compression wood is considerably stronger than normal wood. Sonntag (1904) confirmed that the compression strength of fresh spruce is (44%) higher than that of normal wood.

The objectives of this paper are to find out the limits of compression strength parallel to grain of spruce wood with present reaction compression wood, to describe the strength for individual stem zones, and to create models which would describe the variability of wood compression strength parallel to grain along the radius and the stem height.

## MATERIALS AND METHODS

We have selected a sample spruce (*Picea abies* [L.] Karst.) where the presence of reaction wood was anticipated. The tree was selected in the Křtiny Training Forest Enterprise Masaryk Forest – Mendel University of Agriculture and Forestry in Brno, Habrůvka Forest District, area 164 C 11. The average annual temperature in this locality is 7.5°C and the average annual precipitation is 610 mm.

The tree stem axis was diverted from the direction of the gravity. The axis was diverted in one plane only and the diversion angle at the stem base was 21°. The tree was 110 years old and its total height was 33 m.

Logs (20 cm high) were taken at various heights (6, 8, 10, 12, 15, 18, 20 and 22 m) and the directions of measurements were marked on them. Then, blocks

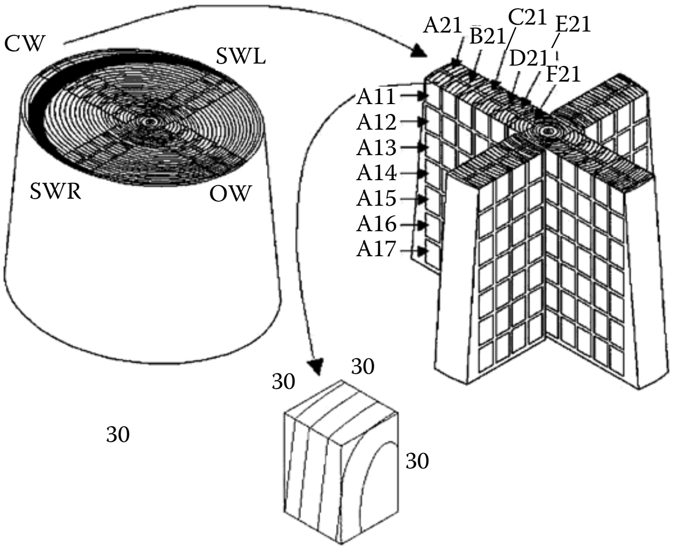

Fig. 1. A diagram of the production of a sample out of the log and the dimensions of the sample (CW – compression zone, OW – opposite zone, SWL and SWR – side zones)

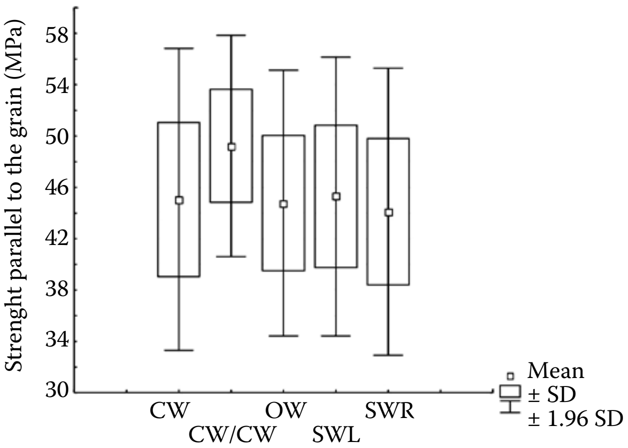

Fig. 2. A box graph, wood compression strength parallel to grain (MPa) for individual stem zones (CW – compression zone, CW/CW – samples with present compression wood, OW – opposite zone, SWL and SWR – side zones)

of wood were sawn out of the logs for individual zones (a block of CW – compression wood zone, CW/CW – a sample containing 25% of compression wood at minimum, a block of OW – opposite zone, and two blocks from side zones, i.e. SWL and SWR). The blocks were then dried in the chamber kiln until the final 12% wood moisture content was achieved. After drying, samples with these dimensions were made: 30 ± 0.5 mm long, 20 ± 0.5 mm wide and 20 ± 0.5 mm thick (Fig. 1). It was necessary that the samples were of a special orthotropic shape. The maximum allowed divergence of rings was set to 5° for testing, the maximum allowed divergence of fibres was also set to 5°. Each sample was marked so that an exact identification of the position in the stem was later possible.

The wood compression strength parallel to grain was examined using the universal testing device ZWICK Z 050 (according to Czech national standard ČSN 49 0110.). To define the influence of the compression wood presence in the sample on the wood density, the sample fronts were digitalized using an EPSON scanner (Epson Perfection 1660 Photo). The parameters of scanning were: colour image with 600 dpi resolution. The digital images of the fronts were used in LUCIA application. The application defined the spot where compression wood is present. It compared the entire sample area with the defined compression wood. The proportion of pixels with compression wood in the entire image gave us the final result of the proportion of compression wood in the sample. The samples from the CW zone which contained min. 25% of compression wood are marked as data file CW/CW in calculations.

Table 1. Results of Tukey's test based on multiple comparison of wood compression strength parallel to grain ($P < 0.05$ statistically significant difference, $P > 0.05$ statistically insignificant difference)

| Zone | CW | OW | SWL | SWR |
|---|---|---|---|---|
| CW | | 0.72 | 0.97 | 0.61 |
| OW | 0.72 | | 0.54 | 0.99 |
| SWL | 0.97 | 0.54 | | 0.45 |
| SWR | 0.61 | 0.99 | 0.45 | |

The average ring width in the sample was set in compliance with ČSN 49 0102 standard. The width was measured using a stereo magnifier (Nikon SMZ 660) (Rybníček et al. 2007).

## RESULTS

The box graph (Fig. 2) shows that the differences in wood strength between the zones are very small. The compression zone (CW) with the value of 45 MPa does not differ much from the remaining zones: OW (44.78 MPa), SWL (45.30 MPa) and SWR (44.75 MPa). The samples with present compression wood (CW/CW) manifest slightly higher compression strength reaching the value of nearly 50 MPa. The statistical examination did not confirm any statistically significant differences in the wood strength in individual zones (Table 1). Table 2 presents the descriptive statistics for the compression strength parallel to grain in individual zones and heights.

The influence of the position in the stem (the radius and the height) seemed to be statistically significant for the compression parallel to grain. The heights of 22 m, 10 m and 12 m are statistically significant for the CW zone; only the height of 22 m is statistically significant for the OW zone; predominantly the heights of 8 m and 10 m are statistically significant for the SWL zone; and the heights of 6 m, 8 m and 15 m are statistically significant for the SWR zone. The influence of the stem radius seems to be more important. There were statistically significant differences between all rings in all zones. No statistically significant differences in the remaining zones (OW, SWL and SWR) were found near the pith and in the stem perimeter (SWL and SWR).

The influence of the ring width on wood strength is exhibited in all the zones as a decrease in wood strength with the increasing ring width. Fig. 3 clearly shows that the trends are very similar in all the zones. There are two obvious groups of data in the models. The first group contains the data in the area of the central part of the stem. Here, the

Table 2. Descriptive statistics of the strength parallel to grain for individual heights and zones

| Height (m) | Statistical variable | Zone | | | | |
|---|---|---|---|---|---|---|
| | | CW | CW/CW | OW | SWL | SWR |
| 22 | N | 12 | 6 | 15 | 10 | 9 |
| | mean (MPa) | 49.68 | 53.02 | 47.97 | 46.68 | 44.13 |
| | variance (MPa)$^2$ | 14.58 | 1.38 | 7.53 | 2.50 | 3.31 |
| | coefficient of variation (%) | 7.69 | 2.22 | 5.72 | 3.39 | 4.12 |
| 20 | N | 19 | 16 | 16 | 15 | 15 |
| | mean (MPa) | 46.13 | 45.39 | 42.73 | 43.93 | 44.24 |
| | variance (MPa)$^2$ | 21.84 | 22.25 | 6.46 | 12.27 | 4.25 |
| | coefficient of variation (%) | 10.13 | 10.39 | 5.95 | 7.97 | 4.66 |
| 18 | N | 27 | 16 | 16 | 22 | 15 |
| | mean (MPa) | 45.88 | 47.22 | 45.16 | 45.92 | 47.66 |
| | variance (MPa)$^2$ | 8.44 | 4.25 | 15.97 | 1.63 | 4.69 |
| | coefficient of variation (%) | 6.33 | 4.37 | 8.85 | 2.78 | 4.54 |
| 15 | N | 27 | 17 | 23 | 22 | 25 |
| | mean (MPa) | 44.14 | 45.83 | 45.59 | 42.87 | 51.31 |
| | variance (MPa)$^2$ | 10.48 | 5.92 | 10.11 | 5.90 | 10.59 |
| | coefficient of variation (%) | 7.33 | 5.31 | 6.98 | 5.6 | 6.34 |
| 12 | N | 40 | 17 | 23 | 20 | 25 |
| | mean (MPa) | 42.96 | 47.73 | 44.35 | 43.87 | 45.12 |
| | variance (MPa)$^2$ | 28.79 | 11.47 | 17.76 | 11.95 | 23.90 |
| | coefficient of variation (%) | 12.49 | 7.10 | 9.50 | 7.88 | 10.84 |
| 10 | N | 44 | 12 | 31 | 28 | 23 |
| | mean (MPa) | 42.98 | 47.86 | 44.86 | 41.84 | 46.96 |
| | variance (MPa)$^2$ | 20.00 | 13.91 | 40.24 | 6.75 | 24.08 |
| | coefficient of variation (%) | 10.40 | 7.79 | 14.14 | 6.21 | 10.45 |
| 8 | N | 61 | 22 | 40 | 39 | 47 |
| | mean (MPa) | 45.54 | 52.20 | 44.30 | 49.94 | 41.62 |
| | variance (MPa)$^2$ | 43.01 | 8.62 | 25.77 | 32.88 | 19.76 |
| | coefficient of variation (%) | 14.40 | 5.63 | 11.46 | 11.48 | 10.68 |
| 6 | N | 67 | 27 | 40 | 46 | 58 |
| | mean (MPa) | 45.59 | 53.90 | 43.67 | 45.41 | 39.94 |
| | variance (MPa)$^2$ | 77.10 | 11.34 | 52.17 | 61.94 | 27.40 |
| | coefficient of variation (%) | 19.26 | 6.25 | 16.54 | 17.33 | 13.11 |
| Σ | N | 297 | 133 | 204 | 202 | 217 |
| | mean (MPa) | 45.06 | 45.39 | 44.78 | 45.30 | 44.75 |
| | variance (MPa)$^2$ | 36.06 | 55.99 | 27.85 | 30.69 | 68.36 |
| | coefficient of variation (%) | 13.33 | 14.98 | 11.79 | 12.63 | 18.48 |

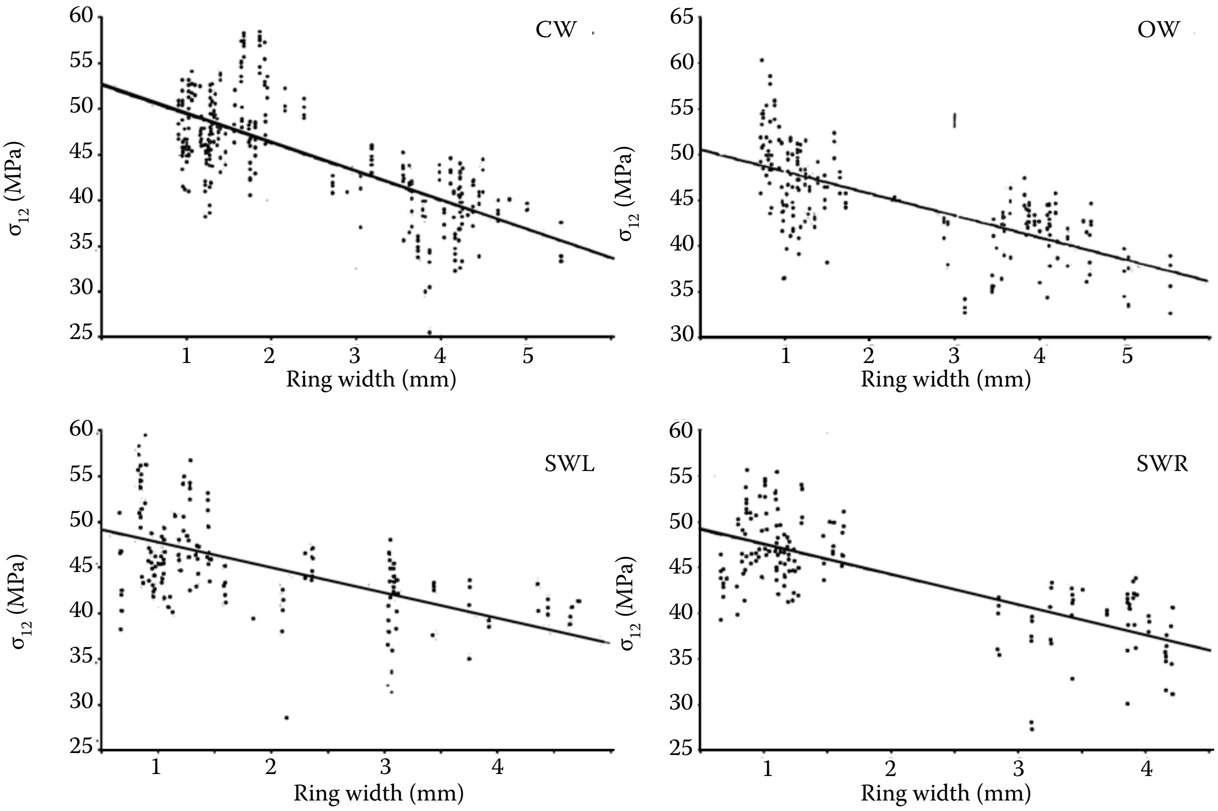

Fig. 3. The influence of the ring width on wood strength for individual stem zones (w = 12%)

wood strength ranges around 40 MPa. The second group of the data is related to the strength found in the stem perimeter. The strength is higher in these parts and ranges between 45 MPa and 50 MPa. The strength increase corresponds with the difference in wood structure between the central and the perimeter stem parts. Higher values of strength (55 MPa) in the CW zone can be seen for the ring width of 1.8 mm. Such strength corresponds to compression wood. The established functions, equation coefficients, and the correlation coefficient of the selective and the basic sample are presented in Table 3. The correlation coefficient of the selective sample ranged between 0.321 and 0.538, which confirms a middle level of dependence of wood strength on the ring width.

All the measured data was used to create 3D models (Fig. 4) describing the dependence of the compression strength parallel to grain on the position in the stem. The influence of the radius is clearly obvious for all the zones. This corresponds to the outcomes of the statistical examination using ANOVA. In the CW, SWL and SWR zones there is an evident increase in wood strength in the central part of the stem, i.e. in the first 40 years. In the following years, there is a slight increase and in the last years stagnation comes. Only in the CW zone there is a distinct decrease in wood strength in the stem perimeter. In

Table 3. The resulting functions for the model of compression strength parallel to grain in dependence on the ring width

| Zone | Function | Coefficient of determination | | Coefficients | |
|---|---|---|---|---|---|
| | | sampling | basis | *a* | *b* |
| CW | $y = a + bx$ | 0.487 | 0.483 | 52.61 | –3.15 |
| OW | $y = a + bx$ | 0.487 | 0.473 | 50.58 | –2.41 |
| SWL | $y = a + bx$ | 0.321 | 0.312 | 50.47 | –2.75 |
| SWR | $y = a + bx$ | 0.538 | 0.533 | 50.74 | –3.27 |

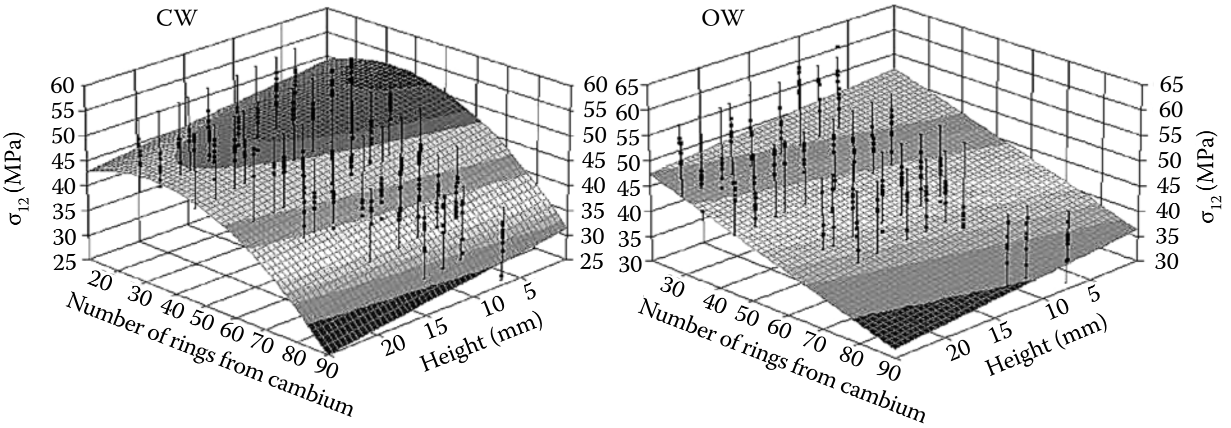

Fig. 4. The resulting functions for the model of wood strength dependence on the position in the stem

the OW zone the increase in wood strength is linear along the entire stem radius.

With the increasing stem height, the wood strength in the CW, OW and SWL zones decreases. Only in the SWR zone the trend is increasing. A possible explanation for the inverted trend is the lower number of data with a higher dispersion of values, or missing data from lower heights. The resulting functions of the selected models, the equation coefficients and the correlation coefficients are presented in Table 4. The values of the correlation coefficients range between 0.52 and 0.63, which confirms a middle up to a high level of dependence of the wood strength on the position in the stem.

## DISCUSSION

As wood is used as a construction material, several vital factors to evaluate its quality have to be considered; and these are not only its physical properties and imperfections, but also its strength properties (Palovič, Kamenický 1961). Compression strength parallel to grain of normal wood is usually stated to be between 34 and 52 MPa (Frühwald et al. 1986; Niemz 1993; Požgaj et al. 1997). The strength in the OW, SWL and SWR zones was around 45 MPa, which corresponds with the published values. Most authors agree that compression wood has higher strength than normal wood (Timell 1986; Frühwald et al. 1986; Gindl 2002). The wood compression strength parallel to grain in the CW zone was also 45 MPa, therefore the statistically significant variance in the middle values of strength between individual zones was not confirmed. However, the strength of compression wood (the samples with at least 25% of compression wood present – the CW/CW zone – were used) was higher, the value being 49.94 MPa. This value corresponds to the data for the compression wood of spruce (*Picea abies*) with 12% of moisture content published by Gindl (2002) and Horáček et al. (2003). The higher strength of compression wood is caused by higher wood density, which is predominantly brought about by the presence of thick-walled compression tracheids. Therefore, it is possible to reject conclusions of Bernhart (1985), who reported lower compression strength for wood with present compression wood. The lower value of strength in his results was probably also affected by the lower wood density with present compression wood (although the difference between normal wood and wood with present compression wood is 8 kg/m$^3$).

Table 4. The resulting functions for the model of wood strength in dependence on the position in the stem

| Zone | Function | Coefficient of determination | | Coefficients | | | |
|---|---|---|---|---|---|---|---|
| | | sampling | basis | *a* | *b* | *c* | *d* |
| CW | $z = a + bx + cy + dy^2$ | 0.630 | 0.625 | 45.65 | –0.254 | 0.417 | –0.006 |
| OW | $z = a + bx + cy$ | 0.539 | 0.532 | 56.52 | –0.185 | –0.223 | |
| SWL | $z = a + bx + cy + dy^2$ | 0.518 | 0.507 | 49.79 | –0.379 | 0.252 | –0.005 |
| SWR | $z = a + bx + cy + dy^2$ | 0.559 | 0.549 | 40.41 | 0.299 | 0.241 | –0.004 |

Palovič and Kamenický (1961) described the significant dependence of compression strength parallel to grain on the percentage of late wood. They found out that with an increasing percentage of late wood the compression strength grows. Assuming that the percentage of late wood is related to the ring width, it is logical that there was a decrease in wood strength in all the zones (see Fig. 3). There is a lower percentage of late wood in a wider ring, therefore the wood compression strength is lower. The lower strength of the wood in wide rings can be inferred from the presence of juvenile wood.

The created 3D models (see Fig. 4) unequivocally confirmed the increase in wood strength in the direction from the centre to the stem perimeter. Such a trend corresponds to the results presented by Palovič and Kamenický (1961), also for spruce. As far as the stem height is concerned, the decreasing trend was confirmed for the CW, OW and SWL zones. An inverted trend was found only for the SWR zone. The inverted trend might have been caused by missing values from lower stem heights. Palovič and Kamenický (1961) stated that the compression strength parallel to grain corresponds to macroscopic features, i.e. the ring width and the percentage of late wood. Their conclusions can be accepted, as also in the case of the sample tree we can see the same relationships of dependence. Especially the variability of the ring width and the late wood percentage along the radius considerably affect the integral physical property – wood density. If wood is to be used as a construction material, the vital factors to consider are, besides its physical properties and imperfections, its strength properties (Palovič, Kamenický 1961).

If wood density has a positive influence on wood strength (Panshin, Zeeuw 1980), it is logical that the increasing wood density along the stem radius (Gryc, Horáček 2007) has to bring about an increase in wood strength along the stem radius. The decreasing wood density along the stem height causes a decrease in the wood strength.

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## Variabilita pevnosti dřeva v tlaku ve směru vláken smrku (*Picea abies* [L.] Karst.) s přítomností reakčního dřeva

**ABSTRAKT**: Cílem práce byla zjistit variabilitu meze pevnosti dřeva v tlaku ve směru vláken smrkového dřeva (*Picea abies* [L.] Karst.). Pevnost dřeva byla zjišťována na vzorcích, které pocházely ze vzorníkového stromu s přítomností reakčního (tlakového) dřeva. Pevnost dřeva byla zjišťována pro jednotlivé zóny kmene (CW, OW, SWL a SWR). Zóna s přítomností tlakového dřeva (CW) vykazovala o něco vyšší hodnoty meze pevnosti dřeva. Rozdíly v mezi pevnosti dřeva v tlaku ve směru vláken nebyly mezi jednotlivými zónami statisticky významné. Ze všech naměřených dat byly pro jednotlivé zóny vytvořeny 3D modely, které popisují pevnost dřeva po poloměru a po výšce kmene. Změna pevnosti po poloměru kmene byla statisticky velmi významná. Byl pozorován zřetelný trend zvýšení meze pevnosti dřeva v prvních čtyřiceti letech. Se zvyšující se výškou kmene dochází k mírnému poklesu pevnosti dřeva.

**Klíčová slova**: mez pevnosti dřeva v tlaku ve směru vláken; smrk; tlakové dřevo; reakční dřevo

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