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COMPARISON OF MECHANICAL PROPERTIES OF THE ELDEST LARCH WOOD CONSTRUCTION WITH OAK WOOD AND SPRUCE WOOD

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ABSTRACT

The paper discusses mechanical properties of timber for structures – most frequently used spruce wood, historically used oak wood and rarely mentioned larch wood. The main focus is on larch wood extracted from the ceiling of an immovable cultural monument from the 17th century – the determination of its age, its historical importance and mechanical properties. Mechanical properties were obtained by the standard tests in compression parallel and perpendicular to the fibres and in bending. The results of tests are compared to the mechanical properties of oak wood, of commonly used spruce wood and of recently felled larch wood.

KEYWORDS: Larch, spruce, oak, historical buildings, immovable cultural monuments, antique wood, historical wood, mechanical properties, wood structures.

INTRODUCTION

Wood is a complex material due to its heterogeneity, anisotropy and natural origin which is often used for construction purposes. However essentially only recently felled and processed wood is being tested for mechanical properties and behaviour so far. There is a lack of tests and studies of the properties of antique wood therefore it is crucial to study its mechanical properties to obtain more information which would help greater the number of successful reconstructions. In historical buildings and trusses in Central Europe, we encounter only a few types of wood. Kyncl J. in Part 5 of (Vinař 2008) states that in the Czech Republic the subject of dendrochronological research (in buildings) are mainly four species of wood which are used systematically and in long-term as building materials – fir, spruce, pine and oak. The share of oak wood is negligible though. The aim of this paper is to compare mechanical properties of antique larch wood with oak wood (which should have similar mechanical properties as larch) and spruce wood, probably the most common wood found in buildings.

Mechanical properties of oak

Values of mechanical properties of oak not classified as historical, i. e. samples that were prepared from recently processed wood, can be found in a variety of sources (Tab. 2). However there is very little data for compressive strength perpendicular to the fibres and so values given by Faculty of Forestry and Wood Technology in Brno, Czech republic, are also listed in Tab. 2 as a reference.

Only a few references were found for mechanical properties of antique oak. Slánský (2008) tested samples of historical oak wood from the church of St. Ignatius in Prague (300 years old) and from the church of St. John the Baptist in Jalubí near Brno (250 years old) (Tab. 1), both located in Czech Republic.

Tab. 1: Mechanical properties of historical oak.

	Slánský (2008)	Slánský (2010)	Thaler (2013)
Bending strength (radial) ($N \cdot mm^{-2}$)	89.85		93.8
Compressive strength parallel the fibres ($N \cdot mm^{-2}$)	54.28	37.14	47.0
Compressive strength perpendicular to the fibres (radial) ($N \cdot mm^{-2}$)	10.33		
Estimated moisture content (%)	12	35	Not specified
Estimated age (years)	300	250	137

Tab. 2: Mechanical properties of non-historical oak.

	Bending strength (radial) ($N \cdot mm^{-2}$)	Compressive strength parallel to the fibres ($N \cdot mm^{-2}$)	Compressive strength perpendicular to the fibres ($N \cdot mm^{-2}$)
(Požgaj 1993)	85.2	59.8	11.0 (rad)
(Ugolev 1986)	108.0	57.5	11.0 (rad)
(Lysý 1954)	110.0	65.0	11.0 (rad)
(Niemz 1993)	94.0	60.0	11.0 (rad)
(Sedlar 2009)	91.4	53.1	
(Riesco 2011)	97.1	59.4	
(Carmona 2020)	113 or 120		
(Wagenführ 2021)	71 (min 57, max 130)	38 (min 33, max 61)	
(Institute 2007)	88	61	11.5 (rad)
Fac. of Forestry and Wood Technology	108	57.5	11.0 (rad), 8.5 (tan)
Thaler (2013)	94.5	46.9	

Mechanical properties of larch

Larch is a relatively rare tree in the conditions of the Czech Republic. Hujnak (1986) estimates its share as 1.23% in 1970 and 1.27% in 1980 from the whole range of forest wood. Same situation has been observed in the past, it is also believed there was no construction-wise usable larch wood (*L. decidua*) in Czech Republic before the 18th century. Nožička (1957) believed the first example of cultivation attempts of *Larix decidua* (not necessarily successful for construction purposes) was in Krnov area in the 18. century (South of East Czech republic). However as stated in Juněová (2019) the first larch in Czech Republic was proven to be cultivated in 1671, the origin of the seeds is yet to be determined, but there is a correspondence dated back to 1683 about a delivery of a batch of seeds from Vienna to Třeboň which leads to speculations that the first batch in 1671 was not successful and the saplings died. Still there is a big historical question if it is possible that larch trees were already present in Czech Republic before 1671 as Bohuslav Balbín states seeing them in woods (even though rarely) in his book Miscellanea Historica Regni Bohemiae. However despite known import of seeds, larch wood is rather rare in the 18th century. More frequent occurrence of larch wood began in the 1770s (Křivoklátsko, Zbirožsko, Chodová Planá). Since 1780 larch could be found in many areas of Czech Republic – which doesn't mean that the produced wood was suited for construction purposes or even meant to be used for construction purposes.

The main problem with properties of larch wood is best described by Xin (2020), the literature is limited with respect to larch and engineered wood products. Given that larch wood, although it has excellent properties, is relatively rare to find in the constructions of Central Europe (other materials are used instead), its properties are not properly examined. Alexa (2017) states that *L. sibirica* is the only representative of conifers classified as hardwood and whose hardness is comparable to oak, *L. decidua* however has better strength properties than most other conifers, as well as *L. sibirica*. The values of compressive strength parallel to the fibres range from 25.5 $N \cdot mm^{-2}$ to 75.37 $N \cdot mm^{-2}$ (Tab. 3). Bending strength of larch reported by other authors is listed in Tabs. 4-6, values range from 24.8 to 132 $N \cdot mm^{-2}$.

Sadly, mostly only compressive strength parallel the fibres and bending strength is examined and so there is very little scientific data determining compressive strength perpendicular to the fibres. However Institute of Wood Science in Brno states the compressive strength perpendicular the fibres as 7.3 $N \cdot mm^{-2}$ (mean value), Faculty of Forestry and Wood Technology in Brno further states it as 4.5 $N \cdot mm^{-2}$ (radial) and 6.1 (tangential).

Tab. 3: Compressive strength parallel the fibres of recently processed wood of Larix decidua.

	Compressive strength parallel the fibres ($N \cdot mm^{-2}$)	Note
(Ugolev 1986)	64.50	MC 0%
(Ugolev 1986)	25.50	MC 12%
(Alexa 2017)	59.00	MC 12%
(Jelonek 2009)	57.5	Poland
(Kokociński 2005)	41-81	
(Bergstedt and Lyck 2003)	56.7	average value
(Instutite 2007)	55	
(Zeidler 2022)	45.8	Czechia
(Wagenführ 2021)	55	(min 41, max 81)
Faculty of Forestry and Wood Technology	64.5	

Note: MC – moisture content.

Tab. 4: Bending strength at different moisture content of Larix decidua (Dědic 2009).

Moisture content (%)	Bending strength (radial) ($N \cdot mm^{-2}$)	Bending strength (tangential) ($N \cdot mm^{-2}$)
0	106.00	107.14
24	35.83	36.93

Tab. 5: Bending strength at different MC of Larix decidua (Bergstedt and Lyck 2003).

MC (%)	Early wood	Late wood
9	48.30	259.00
> 30	25.80	104.70

Note: MC - moisture content.

Tab. 6: Bending strength of larch by other authors.

Region	Bending strength ($N \cdot mm^{-2}$)	Note
(Bergstedt and Lyck 2003)	82.0	Leningrad region
(Bergstedt and Lyck 2003)	104.5	Komi Republic
(Bergstedt and Lyck 2003)	132.3	East Siberia (Jakutia)
(Bergstedt and Lyck 2003)	98.5	average value
(Kokociński 2005)	65-132	
(Jelonek 2009)	24.8	Poland
(Fruhwald 2007)	92.4	
(Chui 1995)	69.62	Maine, USA
(Chui 1995)	50.74	Nova Scotia, Kanada
(Chui 1995)	64.28	PEI, Kanada
(Institute 2007)	95	
(Cukor 2019)	87	Orlické hory, Czechia
(Wagenführ 2021)	95	(min 64, max 132)
Faculty of Forestry and Wood Technology	112	

Mechanical properties of spruce

Spruce wood is commonly used in wood constructions nowadays and even throughout history. Yet there is very little research done on old spruce wood used in historical buildings (Tab. 7). Mechanical properties of recently processed spruce wood can be found in Tab. 8.

Tab. 7: Mechanical properties of historical spruce.

	Bending strength (radial) ($N \cdot mm^{-2}$)	Compressive strength parallel the fibres ($N \cdot mm^{-2}$)	Estimated age (years)
(Thaler 2013)	75.5	34.2	220
(Thaler 2013)	106.3	49.0	220
(Sonderegger 2015)	75.6		120-150

Tab. 8: Mechanical properties of non-historical spruce.

	Bending strength (radial) ($N \cdot mm^{-2}$)	Compressive strength parallel the fibres ($N \cdot mm^{-2}$)	Compressive strength perpendicular to the fibres ($N \cdot mm^{-2}$)
(Kotalík 2010)	58.57	42.1	
(Požgaj 1993)	50-130 (avg. 70.4)		
(Ugolev 1975)	79.5		

(Lexa 1952)	64,7		
(Broumovský 1991)	78		
(Adámek 2008)		70	
(Wagenführ 2021)	78 (min 49, max 136)	50 (min 33, max 79)	
(Institute 2007)	78	50	4.1 (rad)
Faculty of Forestry and Wood Technology	80	44.4	3.4 (rad), 4.0 (tan)
(Thaler 2013)	82.7	39.9	
(Sonderegger 2015)	81.2		
(Niemz 2004)	39.97-52.36		
(Zeidler 2022)		36.1	
(Zeidler 2022)		31.0	
(Zeidler 2022)		34.7	

MATERIAL AND METHODS

Origins of the larch wood

Examined ceiling beam used for samples preparation originates from a ceiling construction of the ground floor level premises of the old town hall situated in Stankov, Czech Republic. This building is recognized as an immovable cultural monument and registered in the Central list of cultural monuments of the Czech Republic under registration number 42065/4-2218.

Both obtained beams were dendrochronologically tested by Kyncl (2017) in Brno. The tests proved the wood to be a *Larix decidua* from south part of West Bohemia, Pilsen Region. It can be dated to the years 1793/4, which resembles the date of the fire damage to the object in 1794 and proves the wood was specifically felled for the reconstruction purposes (Fig. 1).

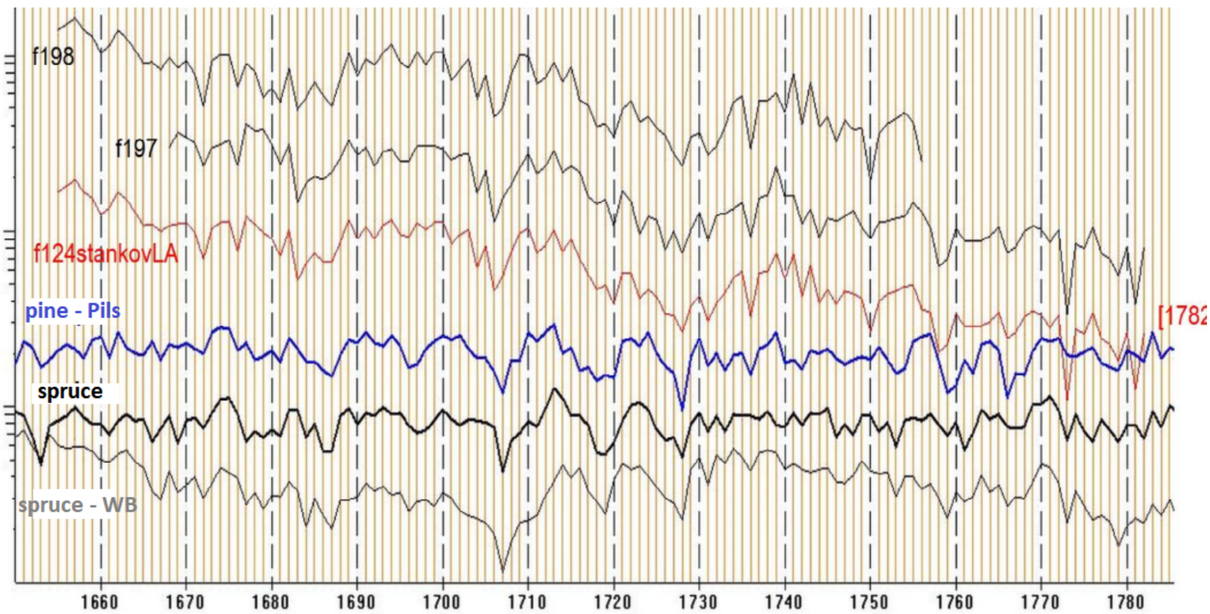

Fig. 1: Dendrochronological comparison of larch samples obtained from ceiling beams from Stankov (upper 3 curves – f198 and f197 are tested samples, f124stankovLA is an annual series curve, obtained from samples 198 and 197 for comparison purposes) with conifers of Western Bohemia (pine, spruce) of given time period from J. Kyncl's laboratory database.

One of the trees is believed to be more than 100 years old in the time of felling meaning it was planted around 1668 (Tab. 8), about 3 years before the first known larch seeds were planted in Czechia (see above). This all makes it the oldest known larch decidua wood sample in Czechia and the first example of successful grown larch decidua for construction purposes in Czechia.

The ceiling beam was extracted during the last of many reconstructions of the building which was caused mostly by the spread of *Serpula lacrymans* and construction damages related to the wood degradation. The part of the ceiling beam, that was used for the preparation of the samples, was intact therefore no fungi was present as the original damaged ceiling beam had to be removed with at least another half a metre of fungi-free beam.

Tab. 8: Results obtained by dendrochronological testing of both larch wood beam samples from Stankov.

Number of beam	Number of annual rings	The last annual ring	Date of felling	**Date of planting**
1	114+11	1782	1793/4	**1668**
2	101	1756	-	**1655**

Origins of the spruce wood

Spruce wood was also tested. About 30 samples of 50 years old spruce felled in 2008 were ordered from local sawmill. Original location of the trees is Novotniky, South of Pilsen region. These samples were used to obtain local spruce values and to compare values to non-local spruce described in literature.

Selection and production of samples

Selected pieces of the larch ceiling beam were stored in well-ventilated storage. The storage conditions correlated with the conditions in the old town hall. Approximately 2 cm of mass around the perimeter was removed from the ceiling beams prior to sample production as this marginal wood was quite certainly affected by atmospheric corrosion and other influences. The leftover wood was cut on slats of dimension 20 x 20 mm and prepared for further selection. Only slats that had approximately the same number of annual rings and didn't show any knots were selected. Further only slats that could be used for a compressive strength test perpendicular to the fibres and parallel to the fibres were selected. For the compressive strength test perpendicular to the fibre and parallel to the fibres samples of size 20 x 20 x 20 mm were prepared. For three-point bending test samples of size 20 x 20 x 300 mm were made. The amount of wood was enough for carefully choosing about 25 samples well suited for testing. For each test 6 samples were used (thus 6 for compressive parallel to the fibre, 6 for compressive perpendicular to the fibre rad/tan direction each, 9 samples for bending). Same amount of samples was used for spruce wood. All testing was performed in accordance with CEN/TC 124: Timber structures standards.

Moisture content measurement

Before starting the tests, all samples were weighed on laboratory scales and measured with a calliper. At the end of the tests, the approximate moisture content of each test specimen was measured using a Testo 606-2 set to measure the moisture content. The average moisture content of all samples was 7.5% (max. 8.9%, min 6.3%).

The average moisture of spruce samples was 11,67% (max. 14,0%, min. 10,1%).

In both cases moisture of all samples was measured after performing tests to prevent distortion of the results by puncture holes left by Testo 606-2.

Compressive strength test

The test to obtain the compressive strength for parallel to the fibres and perpendicular to the fibre in rad/tan direction was done by applying pressure by displacement load (4 $mm \cdot min^{-1}$) on the specimen until material strength limit was clearly visible on the continuously drawn graph. Tests performed in CTU's workshops had load strength and displacement as the outcome which required the calculation of compressive strength. For this purpose, a strength calculation Eq. 1 was used:

$$\sigma = \frac{F_u}{A_s} \frac{[N]}{[mm^2]} \qquad (N \cdot mm^{-2}) \qquad (1)$$

where: F_u – the highest stress that the material can withstand without breaking (N), A_s – area affected by the stress F (mm^2).

Bending test

The test to obtain bending strength was done by applying pressure by displacement load (7 $mm \cdot min^{-1}$) located in the middle of the sample. The sample was supported 30 mm from the end sides. The pressure was applied until the material strength limit was clearly visible on the continuously drawn graph. For the purpose of calculation of bending stress (RAD/TAN) the Eq. 2 was used:

$$\sigma = \frac{M_u}{W} \frac{[N.mm]}{[mm^3]} \qquad (N \cdot mm^{-2}) \qquad (2)$$

where: M_u – maximum bending moment ($N \cdot mm$), W – cross-sectional modulus in bending (mm^3).

For the calculation of cross-sectional modulus in bending only cross-sectional edge lengths are required as the specimen has a square-shaped cross section. For the bending moment, a length of arm of action is needed. In this case, the length is measured from support to the middle point of the specimen (120 mm).

RESULTS AND DISCUSSION

Compressive strength test of larch wood

Figs. 2, 3 show stress-displacement curves for compressive strength test parallel to the fibres and compressive test perpendicular to the fibre in rad/tan direction respectively.

Results of compressive strength are shown in Tab 9. The value of 58.808 N·mm^{-2} was achieved for a direction parallel to the fibres, and 5.06 N·mm^{-2} and 3.722 N·mm^{-2} for perpendicular to the fibres in tangential and radial directions respectively.

Tab. 9: Measured values for compressive strength test of larch wood from Stankov.

	Compressive strength (N·mm^{-2})		
	Parallel the fibres	Perpendicular (TAN) to the fibres	Perpendicular (RAD) to the fibres
Min	54.968	4.537	3.583
Max	62.111	6.953	3.833
Mean	**58.808**	**5.060**	**3.722**
Median	59.430	4.710	3.708
St. deviation	2.410	0.931	0.101
Sharpness	0.839	5.840	-1.550
Skewness	-0.486	2.406	-0.075

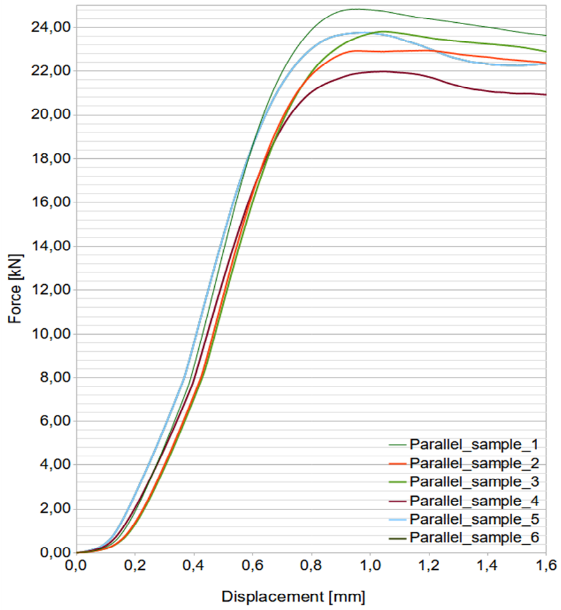

Fig. 2: Stress-displacement curves for the compressive strength parallel to the fibres test of larch wood.

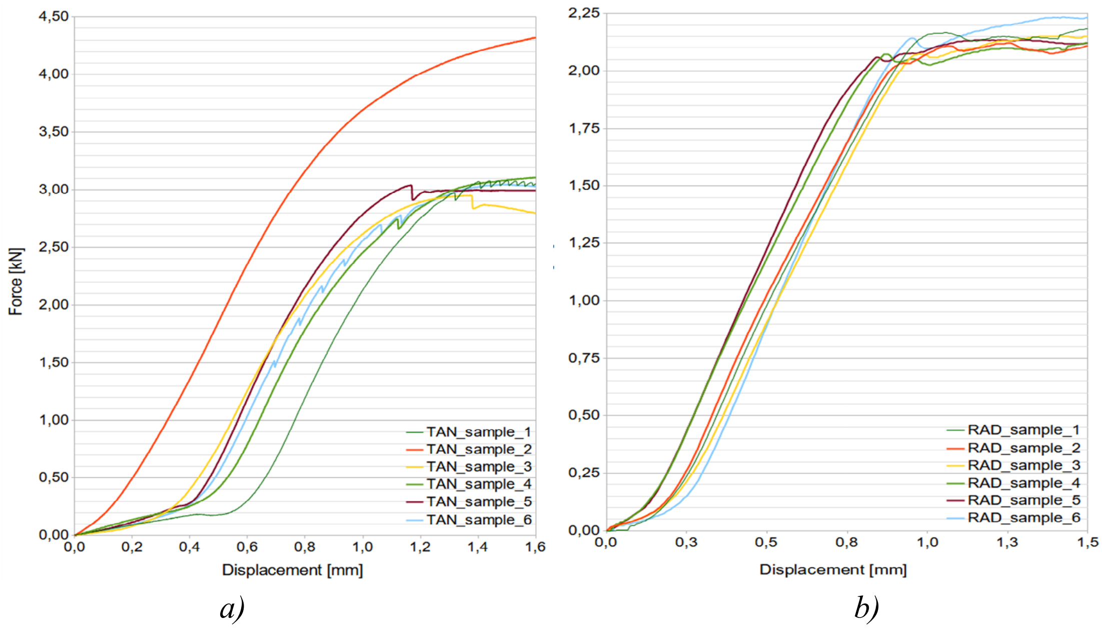

Fig. 3: Stress-displacement curves for compressive strength test of larch wood: a) perpendicular (TAN) to the fibre, and b) perpendicular (RAD) to the fibres.

Bending test of larch wood

Figs. 4 show stress-displacement curves for bending strength. In Tab. 10 is shown the bending strength. The mean value of 88.843 N·mm^{-2} was achieved.

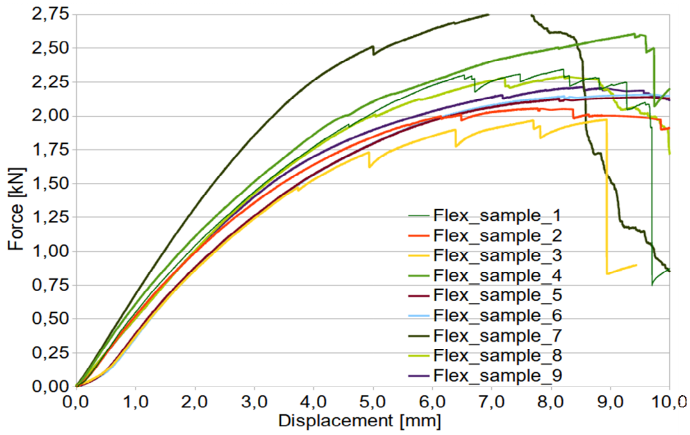

Fig. 4: Stress-displacement curves for bending test of larch wood (TAN).

Tab. 10: Measured values for bending test of larch wood from Stankov.

	Bending strength (N·mm^{-2})
Min	76.755
Max	108.179
MEAN	**88.843**
Median	86.053
St. deviation	10.174
Sharpness	0,271
Skewness	0,973

Discussion

Due to deficiencies of the ceiling beam and limited source of antique wood, not all specimens were made with the direction of annual rings perfectly parallel. Also, the humidity of specimens influences the behaviour and properties of wood, the higher the humidity is, the lower is the strength of the material. Tested larch specimens had a low humidity rate of only approx. 7.5%. The results of testing can be compared to values of larch from literature (Tabs. 3-6), the overall average values for each wood can be seen in Tab. 12.

There are not many sources regarding strength perpendicular to the fibres. The average values are 6.1 N·mm^{-2} in tangential direction and 4.5 N·mm^{-2} in radial direction meaning the tangential direction is superior to radial direction. The results of tests on antique larch follow the same tendency while the strength of antique wood is weaker by 17.3% in tangential direction and 17.01% in radial direction.

However the strength parallel to the fibres is superior to both strengths perpendicular to the fibres with the strength of antique wood 6.8% better than the average compressive strength of other authors. Bending strength is also better in antique wood by 2% than recently felled wood.

Antique larch wood being stronger than average value of data of other authors in bending strength and compressive parallel to the fibres is an interesting outcome. However some sources state higher average values for both properties than overall average value stated in Tab. 12. This leads to antique larch wood possibly having slightly worse characteristics, specifically 20.6% worse in bending strength and 8.8% worse in compressive strength than values given by Faculty of Forestry and Wood Technology in Czech republic or 9.8% worse in bending strength but 3,7 % better in compressive strength than values of Bergstedt and Lyck (2003).

Tests performed on spruce wood

Similarly compressive and three-point bending tests were performed on spruce samples. Results achieved by experiments on recent spruce samples are shown in Tab. 11.

Tab. 11: Mechanical properties of recent spruce 11,6% of moisture content.

Spruce, recent	Value measured ($N \cdot mm^{-2}$)
Bending strength	64.92
Compressive strength parallel the fibres	31.293
Compressive strength perpendicular to the fibres (radial)	4.293
Compressive strength perpendicular to the fibres (tangential)	5.41

Results obtained by testing spruce wood from West Bohemia region are slightly lower than average results (Tab. 12) with bending strength 7.65% and compressive parallel to grain 29.2% weaker but with compressive perpendicular to grain stronger by 35.25% in tangential direction and 26.26% in radial direction. These differences might be caused by slightly different moisture content, by growth rate represented by presence of annual rings (testes samples had approximately 7-8 annual rings each), or even by size of used samples. Overall the results are consistent with the data provided by other authors.

Tab. 12: Comparison of larch, oak and spruce wood – recent and antique (average values).

	Spruce recent	Spruce antique	Oak recent	Oak antique	Larch recent	Larch antique
Bending strength (RAD) ($N \cdot mm^{-2}$)	70.3	85.8	99.77	91.82	87.01	88.843
Compressive strength parallel to the fibres ($N \cdot mm^{-2}$)	44.2	41.6	57.42	54.28	55.04	58.808
Compressive strength perpendicular to the fibres (radial) ($N \cdot mm^{-2}$)	3.4	-	11.00	10.33	4.5	3.722
Compressive strength perpendicular to the fibres (tangential) ($N \cdot mm^{-2}$)	4.0	-	8.5	-	6.1	5.06

CONCLUSIONS

According to Tab. 12, the comparison of strength of spruce, oak and larch wood, it is evident that in the buildings rarely used oak wood has the most favourable mechanical properties, which are comparable for recent and antique oak wood. Larch wood is close to the values of oak wood – with compressive strength parallel to the fibres of antique wood even exceeding average value of recent and antique oak. Spruce, now practically the most used wood, differs from oak and larch in the order of tens of N·mm^{-2}.

As already stated, antique larch has better values of bending strength and compressive strength parallel to fibres by 2% and 6.8% respectively than average recently felled larch. When compared to one of the hardest and most durable types of wood used in constructions – oak – mechanical properties of antique larch are mostly lower: almost 11% in bending strength, about 66% in compressive strength perpendicular to fibres in radial direction, 40.5% in tangential direction. Surprisingly, larch is 2.4% stronger in bending strength in comparison with recent oak. The results are quite similar in comparison with antique oak – antique larch is 3.3% weaker in bending strength, 64% weaker in compressive strength perpendicular to the fibres in radial direction but 8.3% stronger in compressive strength parallel to the fibres. The significant difference in both compressive strength perpendicular to fibres in radial and tangential direction is mainly caused by the difference between coniferous and deciduous wood type as coniferous wood tends to have stronger tangential direction while deciduous trees tend to have stronger radial direction. This can be very well seen in results for spruce (Tab. 12). There is a considerable difference in strength of larch and recent spruce wood, but in comparison of compressive perpendicular to the fibres specifically, it is not as significant as the difference between larch and oak – only 9.45% in radial and 26.5% in tangential direction in favour of antique larch. Bigger difference is in bending strength (26.4%) and compressive parallel to the fibres (33%) – again in favour of antique larch. Comparison with antique spruce has similar results: 3,5% in bending strength and 41.4% in compressive parallel to the fibres in favour of antique larch.

These numbers indicate that the tested wood proved to have high-quality mechanical properties that are comparable not only to recently felled larch trees, purposefully grown for construction purposes, but also to the properties of oak – wood with one of the best mechanical properties.

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