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COMPARISON BEECH WOOD TENSION STRENGTH PARALLEL TO GRAIN OF CYLINDRICAL SAMPLES WITH CONICAL AND FUNNEL TAPERING VERSUS STANDARD RECTANGULAR CROSS SECTION SAMPLES

In this paper, the influence of shape samples on tension strength parallel to grain of beech wood have been analyzed. The cylindrical samples with conical tapering and with funnel tapering were used. Both types of cylindrical samples were compared with one-sided tapered standard samples with a rectangular cross-section.

Experimental outcome indicates that cylindrical samples have higher tension strength than rectangular standard ones. Whereas shape of tapering in cylindrical samples (conical or funnel) was not statistically significant. Furthermore the presentation and reanalysis of data concerning use of cylindrical samples made of seven domestic wood species from the doctoral dissertation were performed. Comparison of that data with source data about tension strength of standard rectangular samples, have proven higher tension strength parallel to grain of cylindrical samples.

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Introduction

Tension strength is one of the basic material strength parameter. In the case of steel, tension strength is the most important and about the simplest parameter to be measured. For wood however tension strength test is more troublesome than those for bending and compression strengths. The fibrous structure of wood cause that stretching of wood parallel to grain shows great strength, and stretching across the fibers shows really small. In both cases it translates to large coefficient of variation of tension strength measurements.

This paper is focused on tension strength parallel to grain. This tension strength is so great, that even with properly made base (the thinned part, where rupture should happen during test) of the sample, prepared with use of high quality wood, it is difficult to ensure, that the sample will not rupture in the grip part. To ensure this goal the shape and profile of the sample are very important. Use of available standards resolve this problem only partially. First of all, standards gives somewhat complicated shape of the sample, but they does not provide usable method of making them. Second of all, there are grounds for the hypothesis, that standard shape of the sample (or other reason) understates the value of wood tension strength parallel to grain.

Basis of the hypothesis about understated value of tension strength, results from research carried out by Koczan [2021], as a part of his defended doctoral dissertation. Goal of that dissertation was to find a formula for calculation of bending strength on the basis of measured wood's compression and tension strength. The analysis of source data [among others Krzysik 1978] concerning theoretical models of bending [Kollman 1951, Kollman, Côté 1984] lead to understated predicted value of bending strength (against data of Krzysik 1978, among others). The most probable cause of this state of things may be the undervaluation of values from tension strength tests. Main reason for the undervaluation might be the shape of the standard sample itself.

The goal of this particular research was selection of samples shape destined for tension strength test parallel to grain, that gives possibly the greatest strength in comparison to standard samples.

Tension strength standards

In XIX-th century, the science of the mechanical properties of wood, among others tension strength parallel to grain, has been studied by many scholars [e.g. Gehler 1826, Bevan 1827, Nördlinger 1860]. Even then, the widening of the grip parts of the samples was used to determine this strength – therefore, relatively correct results were obtained. For example, average tension strength parallel to grain of beech wood were, after recalculation to current units, 143 MPa [Gehler 1826]. The intensification of research on tension strength parallel to grain of wood, in the context of proper shape and dimensions of the samples, had been taken in the next decades. This issue had been research by, among others, Bauschinger [1887], Hatt [1906], Warren [1911] and Jonson [1912], who were testing turned samples (cylindrical), also Graf [1938] who were testing different type of samples with rectangular cross-section (of different kinds of tapering). The effect of that work, have been publication of standards about aforementioned strength. Common feature of all of those samples is shape of double oar of elongated samples (their widening at the end, i.e. grip part, and their tapering in the middle, where the destruction due to pure tensile strength should happen), whereas proportion, rounding or shape of the cross-section have not been fully unified till present.

Rectangular base of standard sample 4 × 20 × 90 mm, still popular in East Europe, and described in the current standard GOST 16483.23 [1973] is probably too long to its thickness. Sample, without grip part, is 150 mm long, and its total length is 350 mm (Fig. 1a). Previous standards GOST 6336-52 [1952] (after Perelygin [1957]) and GOST 11493-65 [1970] were practically identical. The same base, 4 × 20 × 90 mm, was recommended in Polish standard PN-D-04107 [1954][1] (Fig. 1b), while thicker by 1 millimeter base 5 × 20 × 90 mm was recommended by newer, but already withdrawn standard PN-D-04106 [1981] (Fig. 1c). Excessive length (90 mm) of thin base means that the planes of the wood rays ideally parallel to the 20 × 90 mm surface are likely to pass to the other side of the 4 mm thick sample. For example standard COMECON (RWPG in Poland) СТ СЭВ 2377-80 [1980] for plywood states that the length of the base of the same thickness of 4 mm, is only 60 mm (Fig. 1d).

[1] Standard PN-D-04107 [1954] has recommended thinner grip parts of samples 18 × 20 × 100 mm than standards GOST 16483.23 [1973], PN-D-04107 [1981], where grip parts has dimensions 20 × 20 × 100 mm (Fig.1b,1a,1c). All 3 standards describes steel pegs, preventing crushing of the wood in grip parts. Changes in dimensions in Polish standards (18 vs. 20 mm and 5 vs. 4 mm) resulted in inaccuracies in the length of the base (94 and 92, not the recommended 90 mm).

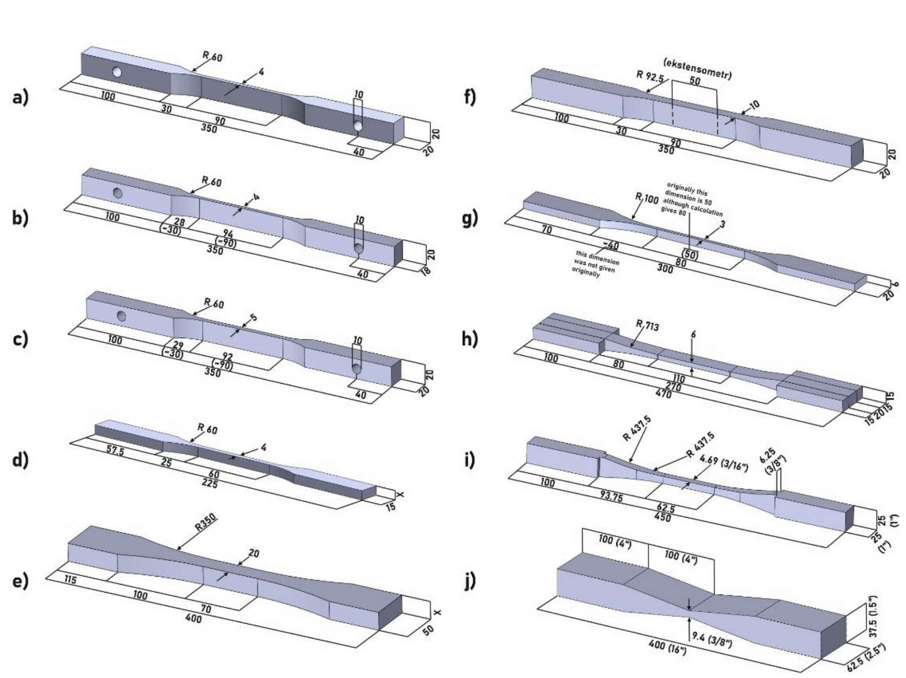

Fig. 1. Examples of different shapes and sizes of samples destined for tension strength parallel to grain tests: a) GOST 16483.23 [1973], b) PN-D-04107 [1954], c) PN-D-04106 [1981], d) smaller (I) plywood sample of CT СЭВ 2377-80 [1980], e) bigger (II) plywood sample of CT СЭВ 2377-80 [1980], f) PN-D-04118 [1959], g) BS 373:1957 [1957], h) DIN 52188 [1979], i) ASTM D 143 [1994, 2014], j) American old wedge-shaped sample Hatt [1906]

Thicker base of 5 mm, as mentioned in the standard PN-D-04107 [1981], or especially 10 mm thick, as mentioned in standard PN-D-04118 [1959][2] (Fig. 1f) is not recommended due to excessive strength of the base in relations to compressed grip part. The cross-section of dimensions 20 × 20 mm of grip part is to small (to narrow) in relation to strong base of cross-section 4 × 20, and especially 5 × 20 mm. The partial solution to this problem is use of samples with narrower base 4 × 18 mm. This, however, significantly complicates production of such double sided tapered samples (almost prismatic) and is against the basic standard GOST 16483.23 [1973] and related standards PN-D-04107 [1981], PN-D-04107 [1954]. The very practice of the sometimes undertaken tapering of samples from 20 to 18 mm proves, that the problem with tension samples is

[2] Standard PN-D-04118 [1959] referred to tension modulus of elasticity and its sample has base 10 × 20 × 90 mm and to grips 20 × 20 × 100 mm (Fig.1f) . Grips did not have steel pegs preventing crushing. Usage of different standard samples for measurement of tension modulus of elasticity and tension strength is impractical and may disturb the outcome of comprehensive endurance tests.

important. The tapering of base cross-section from 4 × 20 mm to 4 × 18 mm is not to be confused with thinning of grip part from 20 × 20 × 100 mm to 18 × 20 × 100 mm that is mentioned in the standard PN-D-04107 [1954] (Fig. 1b).

Certain tolerance of geometrical dimensions, including also small sizes of samples, is demonstrated in standard ISO 13061-6 [2014] which shows dimensions range of rectangular base 5–10 × 10–30 × 50–100 mm. The smallest dimensions of base of tension strength test samples is shown in British standard BS 373:1957 [1957], that recommends base dimensions of 3 × 6 × 50 mm (Fig. 1g). It does not mean that ‘micro tensile testing of wood’ are redundant [Živković and Turkulin 2014].

Another issue is the usage of steel pegs preventing grip part crushing described by standards GOST 16483.23 [1973], PN-D-04107 [1954], PN-D-04107 [1981], and that are not included in tension modulus of elasticity standard PN-D-04118 [1959] (Fig. 1). Such pegs could prevent crushing of wood and destruction of grip part of samples, for example in very soft spruce wood, where it is common even for samples with narrower base of 18 mm. It is difficult to estimate how crushing of grip part undervalues tension strength. In the case of harder woods such as beech wood, there are no need to use steel pegs, and they were not used in this research.

The issue of destruction of grip parts of samples is resolved in German standard DIN 52188 [1979] in a different way (Fig. 1h). The sample in that standard is generally similar, as described in standard GOST 16483.23 [1973], but its grip parts are widened by addition of glued in wooden blocks. The base of German samples has dimensions 6 × 20 × 110 mm. Grip parts, without glued in blocks, have dimensions 15 × 20 × 100 mm, and with added blocks 15 × 50 × 100 mm. The length without grip parts is 270 mm, and total length of samples is 470 mm. Critical remarks about the wood parameter which is tension strength stated in paper [Ozyhar et al. 2012] might stem from inadequacy of such standard sample itself or its impracticality (glued in blocks, big length for a laboratory small samples). Impropriety of DIN 52188 [1979] samples are directly described in paper [Balduzzi et al. 2021]. This sample have been described there as ‘dog-bone sample’, after other authors, although that term is usually used for thick samples destined for stretching strength tests across fibers.

American standard ASTM D 143 [1994, 2014] describes optimized (Fig.1i), yet very complicated shape with double-sided tapering (nearly prismatic) of the tension strength test sample [Markwardt and Youngquist 1956]. Base of this sample is rectangular of dimensions 4.8 × 9.5 × 63 mm. Dimensions of the cross-section of transition part are 6.3 × 25 mm, and grip part are 25 × 25 mm. The original metric dimensions were given according to standard ASTMD 143-94 [1994], although in the textbook [Kollmann and Côté 1984] on page 324 the more precise recalculation from inch system has been provided. The considered sample is so complicated that, in reality, it is rarely used on a larger scale. The proof of that statement is the lack of tension strength parameter values in extensive American database of wood mechanical properties [Green et al. Kretschmann 1999, 2010] and on the internet portal The Wood Database, which creator published the wood atlas [Meier 2015]. If these double-sided tapered samples from standard ASTM D 143-94 [1994] were used more widely, though, the outcome of tests with its usage could be sufficiently authoritative, as suggested by Balduzzi et al. [2021]. Confirmation of that observation might be much earlier results of Graff's research [1938], who used different type of samples with rectangular cross-section and double-sided tapering. However, older American samples [Hatt 1906] were taper on one side (Fig. 1j).

As far as relatively small laboratory tension samples are at least tapered on one side, than the standards for timber does not describe any profiling for the samples. According to work of Kohan, Via and Taylor [2012] the tension strength of samples without tapering might be even 20% lower than samples with even small one-sided tapering. Therefore measurements based on those standards might be relevant only in comparing different timber class or different species. Whereas absolute values of tension strength based on this standard are undervalued and therefore they are not authoritative. Standards EN 408 [2010], PN-EN [2004] provide laconic condition, that the length of the sample between grips has to be no less than 9-times of the larger dimension of the cross-section of construction element. Standard EN-384 [2016] requires that the absolute length of the sample should be 30-times larger than sample thickness ('depth') or be 3600 mm. Standard refers to thickness ('depth') of 150 mm, but smaller thickness is allowed (for example sample of length of 3600 mm, 30-times larger than 120 mm). American standard ASTM D 198-02 [2002] refers to measurements of timber no thinner than 1 inch (standard refers to metric value of 19 mm in one section and to value of 32 mm in another). Total sample length between adjustable grips should be at least 8-times bigger than larger transverse dimension, while in case of stationary grips at least 20-times bigger. Detailed description of American research on tension strength of timber is in paper written by Bohannan [1965], whereas newer work [Ahmad, Bon, Abd Wahab 2010] contains really low values of tension strength of exotic timber (keruing, bintangor, kedondong) based on the standard ASTM D 198-02 [2002], which is most likely related to the presence of a striped arrangement of fibers, which in the tapered part acts like a ordinary deviation of the fibers.

Cylindrical samples for tension strength tests

In this paper, which expands conference publication [Karwat and Koczan 2018], the samples with short base of circular cross-section are being tested. Moreover, the results of the doctoral dissertation [Koczan 2021] concerning such round samples are presented. The motivation for that shape of cross-section stems from two major premises. First is the ease of sample production with process of turning-milling, second is of geometrical nature. Namely the circular cross-section of the sample minimize side surface area of base with set value of cross-section area and sample length. Reduction of side surface area also limits probability of surface defects, especially within sharp edges of the base. The potential validity of such an approach was directly highlighted in the publication [Balduzzi et al. 2021]. New element relative to previous work with cylindrical samples [Karwat and Koczan 2018] is use of funnel-shaped transition from base to grip instead of conical-shaped. Funnel-shaped transition do not have the notches that occur in samples with conical-shaped transition, where the cylinder becomes a cone.

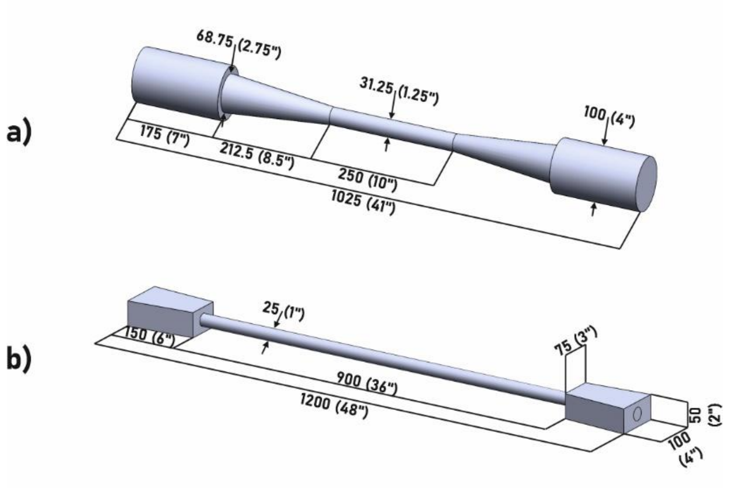

Fig. 2. Examples of historical cylindrical samples for testing the tension strength of wood parallel to the grain: a) Australian turned sample from New South Wales [Warren 1911] , b) American roller sample with reinforced ends [Hatt 1906]

Samples with cylindrical base destined for tension strength testing are not entirely new and its historical Australian [Warren 1911] and American archetype [Hatt 1906] have been presented in conference publication [Karwat and Koczan 2018]. The list of 11 standards presented in that paper (including aforementioned two of Warren and Hatt) have been extended in this paper by 6 new standards (about samples with rectangular cross-section) which have been described above and included into bibliography (list of standards). Cylindrical Australian sample [Warren 1911] (Fig. 2a) somewhat resembled the shape of sample used by authors [Karwat, Koczan 2018], but it had turned (circular) grips and was about four times bigger. The base if that sample had diameter of 32 mm and was 254 mm long [Record 1914]. Cylindrical base transitioned, with conical-shape zone, into diameter of 70 mm, and grips were additionally thickened to diameter of 102 mm. Without grip sample was 686 mm, and total length was 1041 mm. Essentially simpler was cylindrical not-profiled sample described in old American standard [Hatt 1906] (Fig. 2b). The sample was a not-profiled cylinder of 25 mm diameter and total length of 1219 mm. At both ends it was glued in wooden grips 152 mm long each [Record 1914]. Therefore, the base of this sample [part between grips] measured 813 mm.

The turned sample for testing tension strength across grain shown on a photography and technical drawing in handbook [Kollman and Côté 1984] on pages 334 and 335 is worth mentioning. For solid wood, according to the drawing, the base of 10 mm diameter and 20.4 mm length without funnel transition (and 54 mm with) is recommended. Total length of that sample was 125 mm along with thickened grip (also cylindrical). Probably those samples would have even higher performance in comparison to samples with rectangular cross-section than in case of samples destined for tension along the grain. This assumption seems even more vivid if such samples were made in the process of turning-milling, and not in the process of regular turning.

Tension strength parallel to grain of beech wood – review of the literature

Used in research beech wood (*Fagus sylvatica* L.) is one of the strongest wood species of temperate zone and is widely used in wood and furniture sector [Koczan, Kozakiewicz 2016]. It applies to, perhaps even particularly, to tension strength parallel to grain. Beech wood has microporous structure and its properties are more homogenous in comparison to softwoods and ring-vascular heartwoods. Wood rays are extensive, but not as much as belonging to the same family *Fagaceae* ring-vascular oak wood.

The average tension strength of beech wood at the moisture content level of 15% and with density of 730 kg/m^3, according to Krzysik [1978] is 132 MPa (see Tab. 1) and it was measured according to standard PN-D-04107 [1954]. This value is confirmed by Gustafsson's [2010] measurement of beech wood with density of 770 kg/m^3 and moisture content level of 5.5%. The outcome value was 130.4 MPa. Nearly the same value of 131.15 MPa measured for Gregorian beech (*Fagus orientalis* Lipsky) with moisture content of 12%, and performed according to standard ASTM D 143 [2014, 1994], were reported by Ashrafi et al. [2021]. Similar value of 135 MPa is also presented in popular wood atlas Wagenfür [2007].

Table 1. Reference value of strength data according to Krzysik [1978] for seven domestic species of wood that are mentioned in this paper with distinction of tested in this work common beech (*Fagus sylvatica* L.)

Moisture content 15%	Density [kg/m³]	Strength parallel to grain	
		Compression *C* [MPa]**	Tension *T* [MPa]**
Wood species*	Min – Mean – Max	Min – Mean – Max	Min – Mean – Max
Scots pine	330 – **520** – 890	29 – **46** – 78	34 – **102** – 192
Norway spruce	330 – **470** – 680	29 – **42** – 66	39 – **88** – 240
Common oak	430 – **690** – 960	45 – **51** – 56	49 – **88** – 177
European ash	480 – **720** – 940	25 – **47** – 62	33 – **102** – 216
Common beech	540 – **730** – 910	34 – **52** – 82	56 – **132** – 177
Silver birch	510 – **650** – 830	32 – **42** – 83	34 – **134** – 265
Black poplar	410 – **450** – 560	22 – **29** – 47	42 – **76** – 108

* Latin names are given in Table 3
** strength values in MPa were converted from kG/cm^2 =0.0981 MPa

Whereas tension strength value of beech sawn timber, with measurement performed according to standard EN 408 [2010, 2012], gives significantly lower outcome than aforementioned. In Erhart‘s et al. [2018] work, sawn timber with density of 701 kg/m^3 had, at the moisture content level of 8%, tension strength mean value only at level of 77.2 MPa. Similar results have been obtained in earlier work [Erhart et al. 2016] in the measurements of sawn timber with moisture content level of 8%, which after recalculation to 12% were characterized with density of 739 kg/m^3 and mean value of tension strength of 66.7 MPa. Because used timber contained defects and was characterized by high variability of results (min. 15 MPa, max. 132 MPa), then after the samples with largest defects were discarded, the mean value increased to 88 MPa.

Slightly bigger values were obtained in measurements of beech samples without visible defects performed according to standard DIN 52188 [1979] [Ozyhar, Hering, Niemz 2012]. Unfortunately the samples with low as for beech wood density of 640 kg/m^3 were used. The tension strength at three different moisture content levels were accordingly 115.3 MPa (5.9%), 96.7 MPa (11.3%), 83.6 MPa (14.3%).

One of the largest average values of tension strength parallel to grain of 180 MPa is reported in article by Ehrhart et al. [2018] – according to Wagenführ [2007]. However, the value of 180 MPa had to be confused with the actual value of 135 MPa Wagenführ [2007]. Therefore, the reader should be interested in the fact that in this article the average strength was significantly bigger than 180 MPa at mositure content level of 8% and slightly bigger than 180 MPa after recalculation to mosture content level of 12%. However the work of Gašparík, Gaff, Babiak [2017] gives even bigger, ultimate tension strength value of 205 MPa for beech wood. Wherein, the authors probably treated the "ultimate" value here as the maximum value, as well as they have assigned the sample from standard GOST 16483.23 [1973] to standard ISO 13061-6 [2014] by mistake. Furthermore, the authors cited work of [Kúdela 1999], that according to them, gives tension strength of beech wood of 190 MPa.

Materials and methods

Main research material was one board of beech timber of dimensions 52 × 470 × 2600 mm. Timber have been seasoned in two pieces, 1300 mm long each. Next, the pieces have been sawn in two parts in length and three parts in width. The effect were 12 pieces of dimensions 52 × 235 × 430 mm of which 124 beams of cross-section dimensions 20 × 20 and length of 350 mm were made for target samples creation.

As a result of selection 25 beams have been discarded (out of 124), remaining 99 have been divided into 3 groups of 33 pieces each. First group were destined for standard samples (S for 'standard', Fig.3a) and other two were destined for cylindrical samples, one with conical tapering (K for German 'Kegel', Fig.3b) and other with funnel tapering (F for 'funnel', Fig.3c). Standard samples type S were created with use of GOST 16483.23 [1973] standard. The selection of each sample were performed with enormous care, so each group of samples S, K, F had been taken from adjacent timber samples.

Samples type S were made with use of high precision band-saw. Next they were smoothen with belt sander with shape stencil. Typically such samples are created by spindle milling, which can cause destruction of samples 4 mm-thin base. Therefore, typical production process of such samples leads to loss of at least some of them. Use of precision band-saw allowed avoidance of those losses.

Cylindrical samples type K and F have been made with turning-milling machining. Different samples with conical tapering between base and grip were studied earlier [Karwat and Koczan 2018]. In this research it have been decided to test softer, funnel, tapering then conical.

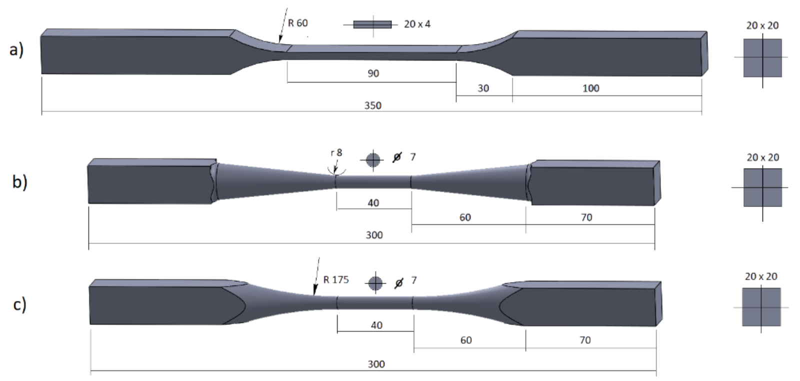

Fig. 3. Dimensions and shapes of samples used for tension strength along the grain tests: a) standard sample type S (GOST 16483.23 [1973] without strengthening pegs), b) cylindrical samples type K (German Kegel) with conical tapering (original created by Karwat, Koczan [2018]), c) cylindrical samples type F with funnel tapering (newest)

Before process of milling samples were placed in special metal mountings (Fig. 4). Turning-milling process have been performed with use of precision lathe for metal with electric spindle for milling placed instead of knife holder (Fig. 5). Technical details have been presented in broader spectrum in earlier work [Karwat and Koczan 2018] in the context of previous research. Only change were newer lathe and new templates for cylindrical samples type K and F (Fig. 6).

Fig. 4. Mounting of the beam (20 mm × 20 mm) in metal grips and mounts of lathe

Fig. 5. Mounting of the sample (type F) in lathe and kinematics of machining. The cutting blade of the milling machine is visible in the middle, a piece of lathe spindle on the left side and milling support (in the bottom) coupled with ball-bearing slider moving along metal template (at the top-left side)

Fig. 6. Stainless steel templates cut out with use of laser and CNC machine, that helped in preparation of samples for tension strength testing (from the top): standard type S, cylindrical with conical tapering type K, cylindrical with funnel tapering type F

Samples of all types, S, K and F, were made with great accuracy, however in the case of slight dimensional differences, the dimension of the cross-section of the smallest part of the base had been noted. For standard samples type S it was width and thickness, and for the cylindrical samples type K and F it was diameters (thickness) in the radial and tangential directions. As a effective diameter the arithmetic mean was taken, which, at the small differences, does not deviate from the geometrical mean:

$$d = \sqrt{d_r d_t} \approx \frac{d_r + d_t}{2} \tag{1}$$

Tension strength tests was performed on endurance machine Instron, that have maximum strength of 100 kN. Feed speed of the head was set, so the sample destruction would happen after 90 s.

In addition the data on tension strength of cylindrical samples type K for 7 domestic species have been presented: Scott's pine, Norway spruce, pedunculated oak, common ash, common beech, silver birch and black poplar. The cylindrical samples with conical tapering (type K) were obtained with turning-milling technique. After that, they were conditioned over the saturated solution of $NaNO_2$, which stabilized moisture equivalent of the samples at level of about 12%. In addition to moisture content and density of tested species, as reference, the data on compression strength was used. The compression strength tests were performed with use of rectangular samples of dimensions 20 × 20 × 60 mm. Results of tension strength measurements of samples type K was compared to source data from Krzysik [1978] for standard samples type S. The standard deviation σ of a single measurement (not the mean) was used as a measure of variability. In the case of Krzysik's source data it was assumed, that obtained by him extreme values (minimum and maximum) differentiate from mean by 5σ. The 5σ criterion is used in contemporary science for maximal possible statistical error for science discoveries [Lyons 2013] and is stronger criterion that as popular 3σ criterion. The assumption made leads to an estimate:

$$\frac{x_{max} - x_{min}}{2} = 5\sigma \quad \longrightarrow \quad \sigma = \frac{x_{max} - x_{min}}{10} \tag{2}$$

The selection of 5σ criterion against 3σ stems from wide dispersion of minimal and maximal values reported by Krzysik. Probably, it is due to the large amount of samples of large variety. Criteria 5σ in Krzysik's work had given better compatibility with standard deviations in Koczan's [2021] data (see further Fig. 9), than 3σ criterion. However, for data of that work, the criterion of 3σ, or even 2.5σ, would suite better (see Table 2). The possibility of estimation of standard deviation in Krzysik's work does not allow to estimate standard error due to lack of information on samples count.

Comparison of three standards of moisture content for wood samples used in research of 8%, 12% and 15% required of use of Bauschinger's formula and reference to current standard of moisture content of 12%:

$$T_{12} = T_W \cdot \left(1 + \alpha_B (W - 12)\right) \tag{3}$$

where: T_{12} – tension strength at moisture content level of 12%, T_W – tension strength at moisture content level of W%, α_B – Bauschinger's factor (for tension strength it was assumed $\alpha_B = 0.015$), W – count of percentage points for absolute moisture content. For the comparative calculations of compression strength, the three times bigger factor $\alpha_B = 0.045$ was assumed.

Table 2. Values of tension strength of beech wood for rectangular and two type of cylindrical samples with conical and funnel tapering

(*Fagus silvatica* L.)	Shape of samples		
	Rectangular	Cylindrical	
Properties of beech wood samples	Standard S	Cone K	Funnel F
Dimension of cross section [mm]	20 × 4	Ø 7.0	Ø 7.0
Gauge lenght [mm]	90	40	40
Density [kg/m^3]	761	764	759
Absolute moisture content	7.84%	7.88%	7.87%
Mean tension strength [MPa]	**172.8**	**196.3**	**193.9**
Standard deviaton [MPa]	31.8	36.9	40.1
Standard error [MPa]	5.5	6.4	7.2
Maximum value [MPa]	235.9	288.8	281.7
Minimum value [MPa]	100.1	102.5	104.8
Number of samples	33	33	31*

* two tension measurements just failed

Results and discussion

Fundamental result of measurement of tension strength of standard beech samples type S and cylindrical samples types K and F have been shown in Tab. 2. Values of tension strength have been compared on chart in Fig. 7. Cylindrical samples (types K and F) were on average about 13% more durable than standard samples (type S). This 13% increase will not change when results will be calculated to different moisture content. Due to small standard error that stems from sufficiently large number of samples (above 30) aforementioned difference might be considered as statistically significant (in the alpha level standard of α=0.05 for a stronger two-sided test). To be more precise, difference in tension strength of cylindrical samples were on average 2.5 times bigger than effective standard error of this difference[3]. Whereas between cylindrical samples with conical tapering (type K) and with funnel tapering (type F) no significant differences in tension strength have been observed.

Measured values of tension strength for samples type S, K, F recalculated to moisture content of 12% were compared on Fig. 8 to beech standard samples type S from Krzysik's work [1978] (see Tab. 1) and also to cylindrical samples type K from Koczan's doctoral dissertation [2021] (see Tab. 3). Krzysik's data were recalculated from moisture content of 15% to 12%, while tension strength from Koczan's doctoral dissertation were referring to standard 12% already (results for second standard of 8% are not shown in this paper due to difficulties in comparison of outcomes from different tests).

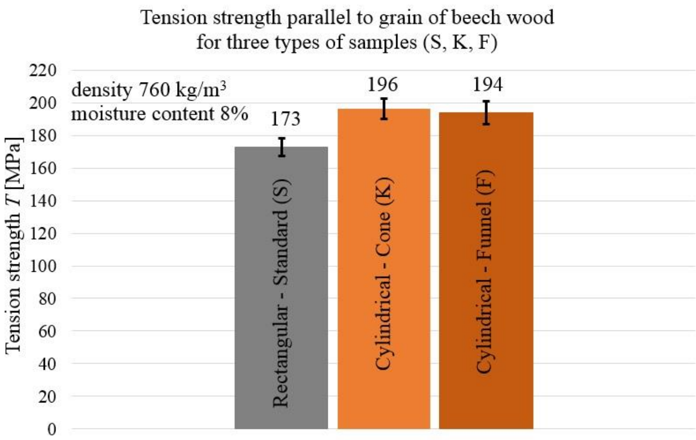

Fig. 7. Comparison of the three main tension test results (with standard errors) of beech wood for samples S, K and F

On Fig. 8 is visible, that outcome from additional sources [Krzysik 1978, Koczan 2021] are significantly lower than those measured in current research. Those lower scores might be explained by two facts: difference in density and difference in shape (standard vs. cylindrical). In comparison to cylindrical samples type F (current research) Koczan's cylindrical samples type K (older research) have lower density by about 60 kg/m^3, which leads to lower tension strength by about 40 MPa. Whereas standard samples type S (current research) are of the same density as cylindrical samples type F (current research), but they

[3] Criteria 3σ and 5σ mentioned in Materials and Methods chapter is not required here, because it is not measurement of completely new parameter, but only measurement of the same parameter with use of different type of samples.

have smaller tension strength by 20 MPa. Using this simplified arithmetic to Krzysik's samples (standard type S – oldest research), the lower density by 30 kg/m^3 should lower tension strength by 20 MPa, which is the same as the addition reduction 20 MPa stemming from samples shape. Estimated in this way effective total reduction in tension strength should be 40 MPa and it is close to real value of 46 MPa. This rough estimate shows logical compliance of two sources: Krzysik's [1978] and Koczan's [2021] with current measurements of beech wood tension and it proves the hypothesis that the strength of cylindrical samples is greater than the standard ones.

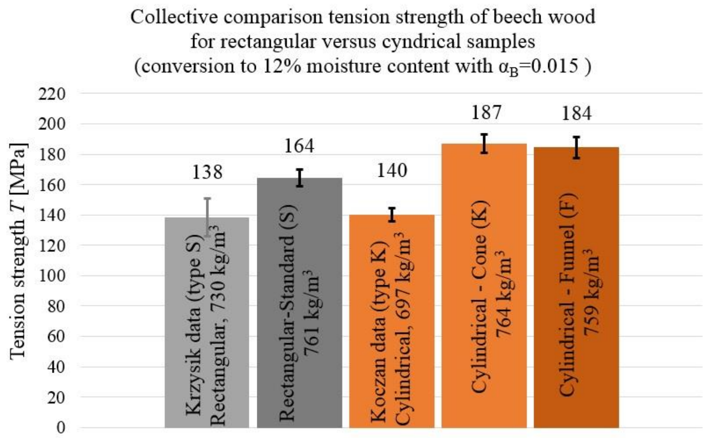

Fig. 8. Comparison of tension strength of standard samples type S and cylindrical samples types K and F with consideration of Krzysik's source data and outcome from Koczan's doctoral thesis. All values are in reference to 12% moisture content standard. The values of standard errors have been shown, and for Krzysik's data estimated standard deviation

Thanks to comparison of Krzysik's [1978] data for the rectangular samples with results for analogical species from Koczan's [2021] work (Tab. 3) the further analysis of issue of samples shape is possible. Tab. 3 contains, alongside with density, tension strength and compression strength values acquired in Koczan's work. The tension strength is in the center of attention, and compression strength is assumed to be a reference that is more reliable than the density itself. In this assumption, data from Krzysik [1978] and Koczan's work [2021] have been summarized in the column graph in Fig.9.

Next, the same data (Tab. 1 and Tab. 3) have been compared in Tab. 4 at the level of rates of tension strength. Rate of tension strength gained on cylindrical samples of Koczan [2021] is bigger by 13.3% with regard to the data gained on Krzysik's [1978] standard samples. However, after taking under consideration the recalculated values of moisture content this difference grows to even 23.1%. This excessively large difference is mostly due to undervaluation of tension strength of ash in Krzysik [1978] (Tab. 1), which, unfortunately, is present in all editions of this handbook. However reliable argument for this mistake is highly overvalued mean tension strength value of 165 MPa which were reported by [Spława-Neyman, Owczarzak 1996/2021 and Wagenführ 2007], basically compatible with Krzysik with another values for ash wood (and not only for ash).

Table 3. Basic data (except bending) for seven domestic wood species (three exotic species have been studied also) from Koczan's doctoral thesis [2021] measured at moisture content level of 12% (level of 8% have been studied also)

Moisture content Standard 12%	Moisture content	Density [kg/m^3]	Strength parallel to grain Compression *C* [MPa]	Strength parallel to grain Tension *T* [MPa]
Wood species	Mean	Mean	Mean ± St. dev.	Mean ± St. dev.
Scots pine (*Pinus sylvestris* L.)	12.25%	511	40.8 ± 3.8	101 ± 13
Norway spruce (*Picea abies* Karst.)	13.18%	490	48.3 ± 3.5	132 ± 17
Common oak (*Quercus robur* L.)	13.20%	686	50.0 ± 4.1	90.1 ± 8.6
European ash (*Fraxinus exelsior* L.)	11.36%	671	47.2 ± 2.9	143 ± 13
Common beech (*Fagus silvatica* L.)	**11.60%**	**697**	**53.0 ± 5.4(1.1*)**	**140 ± 17(4,2*)**
Silver birch (*Betula pendula* Roth)	11.04%	611	57.8 ± 2.8	166 ± 16
Black poplar (*Populus nigra* L.)	11.98%	386	25.7 ± 5.5	74 ± 15

* standard error equal to the standard deviation divided by the root of the number of samples

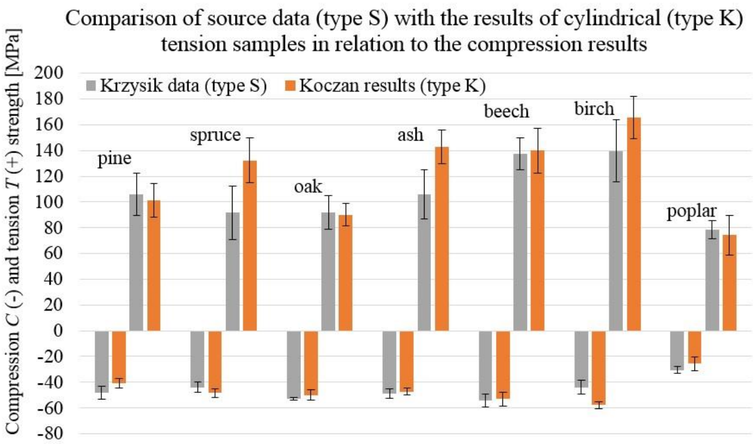

Fig. 9. Data sheet of data by Krzysik [1978] (left columns, moisture content level of 15%) with data by Koczan [2021] (right columns, moisture content level of 12%). Columns directed upwards compares data on tension strength, and those directed downwards compares data on compression strength. The value of standard deviation have been shown, which for Krzysik's data have been estimated with use of formula (2)

Table 4. Comparison of rates of tension strength and compression strength for Krzysik's data [1978] based on standard samples type S in comparison to Koczan's data based on cylindrical samples type K. Relative rate of abovementioned values, simplified, informs how many times cylindrical samples are stronger than standard ones

Moisture content Krzysik data 15% Koczan data 12%	Tension/compression strength ratio Krzysik [1978] Rectangular samples (type S)	 Koczan [2021] Cylindrical samples (type K)	Comparative ratio
Wood species	$x=T/C$	$y=T/C$	y/x
Scots pine	2.21	2.48	1.121
Norway spruce	2.09	2.74	1.308
Common oak	1.73	1.80	1.041
European ash	2.17	3.03	1.398
Common beech	**2.55**	**2.64**	**1.036 (1.125**)**
Silver birch	3.19	2.87	0.899
Black poplar	2.57	2.89	1.125
Mean value	$2.36 \pm 0.18^{*}$	$2.63 \pm 0.15^{*}$	**1.133** $\pm 0.064^{*}$
Mean for 12%**	$2.17 \pm 0.17^{*}$	$2.63 \pm 0.15^{*}$	**1.231** $\pm 0.070^{*}$

* standard error equal to the standard deviation divided by the root of $n = 7$

** converted from Bauschinger formula with coefficients $\alpha_B = 0.045$ or $\alpha_B = 0.015$ respectively for compression and tension.

Analyzed rates of tension strength for beech, without recalculation of moisture content, is only 3.6%. However, after the recalculation, the growth is approximately 12.5%≈13%, which is similar to main measurement performed for this paper.

Conclusion

Both samples types K and F, those with cylindrical base, showed up greater tension strength (on average 185 MPa in reference to 12% moisture content standard) than standard samples type S with rectangular base (164 MPa). This growth of measured tension strength of beech wood samples, that is about 13% (alpha level better than $\alpha = 0.05$) have been confirmed with comparative analysis with Krzysik's data [1978] and with data from doctoral dissertation of Koczan [2021] the second author of this paper. Maximal value of tension strength measured at the level of moisture content of 8% was as high as 289 MPa. Extension of the analysis for another seven domestic wood species proved higher value of tension strength for cylindrical samples (K) over standard rectangular samples (S).

Measured difference in tension strength is not only due to different shapes cylindrical and rectangular of samples base, but also due to different geometrical size of those bases. Length of base have been shortened almost two times, as well as cross-sectional area. Shortening of samples length halved probability of existence of wood defects and fiber twisting (deviation) in measured samples base. The reduction of cross-sectional area increased rate of tension strength of grip to base. By analogy, narrowing old standard samples base cross-section from 4 × 20 mm to 4 × 18 mm have long experimental tradition in Institute of Wood Technology and Furniture (Warsaw University of Life Sciences – SGGW, formerly Department of Wood Technology). This tradition was originally stemming from engineers intuition, and then were proven by experience. However this tradition does not have its reflection in standards regarding to tension strength along fibers, and due to that reason, standard constricted samples, with base cross-section dimensions of 4 × 18 mm, were not taken under consideration in this paper. It cannot therefore be ruled out that such constricted standard samples would be equal to the cylindrical samples.

There was no significant difference in strength within the cylindrical samples between type K with conical tapering and type F with funnel tapering. Lack of that difference might be indication that both types are optimized well enough. Indirect argument for that is compliance of prediction models of bending on the basis of compression strength and tension strength in Koczan's work [2021]. This compliance would be hard to accomplish, if the higher tension strength would not be achieved with use of cylindrical samples type K.

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