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Bending strength of Scots pine wood – relationships between values calculated at different height of the trunk

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Abstract. *Bending strength of Scots pine wood – relationships between values calculated at different height of the trunk*. The aim of the study was to determine relationships found between bending strength recorded at different heights of the trunk, particularly between the breast height section and sections located in other parts of the stem. Field analyses were conducted in 7 mature pine stands (the Regional Directorate of the State Forests in Szczecinek). The material originated from stems of 63 sample trees. Five samples were collected from each trunk, of which one sample represented the breast height level (SI), while the others 20 (SII), 40 (SIII), 60 (SIII) and 80% (SV) tree height, respectively. Each level (section) was represented by two opposite radiuses – eastern and western. Strength testing was performed at moisture content exceeding 30% (above fiber saturation point). Bending strength (BS) of wood from the tested Scots pine trees was around 48 MPa. Strength decreased gradually along the stem. Linear dependencies, confirmed by high linear correlation coefficients, were found between bending strength at breast height and strength determined at other heights of the trunk. Breast height is a representative cross section of the stem. Bending strength determined at this level may be used to model strength in other parts of the stem.

Keywords: heterogeneity of wood, axial variation, breast height diameter

INTRODUCTION

The tree trunk is an elastic biological structure undergoing frequent deformations, e.g. under the impact of wind. Except for extreme phenomena, e.g. windbreaks, these deformations do not cause permanent changes [Tomczak et al. 2012]. Resistance of trees to breakdown is influenced by many factors [Petty, Swain 1985; Peltola, Kellomäki 1993; Ancelin et al. 2004; Nishimura 2005]. Among them a significant role is played by wood properties, including bending strength. The trunk is broken when the total bending moment exceeds maximum bending moment of wood [Zajączkowski 1991]. As it is generally known, the wood tissue is highly heterogeneous. Wood properties vary depending on the location on the stem [Jyske et al. 2008, Tomczak, Jelonek 2013]. Thus its bending strength will be the sum of wood strength in its different parts.

For this reason an accurate biomechanical profile of a tree should be based on an extensive body of empirical material. It may hardly be attained in practice. Thus mathematical modeling is applied, where the behaviour of a system is described using the language of mathematics. Several independent variables correlated with a dependent variable constitute the basis of the model. A tree is a functional system. This means that individual elements of this system (the wood tissue, morphological traits of the tree) form a complicated network of interdependencies. Pazdrowski [1992] analysed interdependencies between mean basic density determined at different heights of a 5–meter bole and obtained high values of correlation coefficients. Similar results were reported by Tomczak et al. [2013a], who analysed relationships between wood density at breast height and density at 20, 40, 60 and 80% tree height. Analogous results were also recorded in relation to compressive strength along the grain [Pazdrowski 1992; Tomczak et al. 2013b]. Jelonek [2013] determined relationships between wood properties and morphological traits of Scots pines growing on forest soils. Compressive strength along the grain (W>30%) correlated with breast height, stem slenderness and relative crown length, while bending strength correlated with breast height diameter, tree height, length of live crown and slenderness ratio. No relationships with morphological traits were found in relation to basic density [Jelonek 2013]. Similarly, no dependencies between wood density and selected parameters of the crown in Douglas fir were found in a study by Wąsik [2010].

It results from the studies presented by Pazdrowski [1992] and Tomczak et al. [2013a, b] for basic density and compressive strength along the grain that prediction may be based on the assumption of an interdependence within the same property. For this reason the aim of this study was to determine relationships found between bending strength at different heights of the trunk, particularly between breast height section and sections located in other parts of the stem.

MATERIAL AND METHODS

Analyses were conducted in the forest districts of Czaplinek, Czarnobór, Łupawa, Miastko (2 sites), Świdwin and Warcino (the Regional Directorate of the State Forests in Szczecinek) (tab. 1). In selected stands (fresh mixed coniferous forest site, quality class I, broken crown closure) sample plots were established, on which 63 sample trees (9 from each plot) were selected based on diameter and height characteristics.

Tab. 1 Characteristics of stands, in which experimental plots were located.

No	Forest district	Stand	Age	Zd	$D_{1,3}$	H	Coordinates	
					[cm]	[m]	N	E
1	Miastko	10 So	84	0,9	34	26	53° 58' 28"	16° 58' 3"
2	Miastko	10 So	89	0,7	36	26	54° 0' 56"	16° 53' 59"
3	Warcino	10 So	86	0,9	31	25	54° 12' 37"	16° 52' 28"
4	Czaplinek	10 So	87	1,0	35	27	53° 37' 35"	16° 11' 57"
5	Łupawa	10 So	83	0,7	37	24	54° 23' 11"	17° 17' 40"
6	Świdwin	10 So	83	1,1	32	26	53° 53' 3"	15° 44' 18"
7	Czarnobór	10 So	82	0,8	31	24	53° 36' 59"	16° 40' 37"

Material for testing of bending strength (BS) comprised 315 samples, five for each sample tree. Samples were located at different heights, the first at breast height ($d_{1.3}$), with the successive samples located at 20 (SII), 40 (SIII), 60 (SIII) and 80% (SV) tree height.

Each level (section) was represented by two opposite radiuses – eastern and western. Samples were adjacently located, along the radiuses, with the first one at a distance of min. 1 cm from the pith. Strength testing was performed at moisture content exceeding 30% (above fibre saturation point), i.e. under conditions simulating the state of a growing tree. Threshold moisture content of membranes was provided by immersion of samples in water until they reached dimensional stability, i.e. the time when increment in individual dimensions of samples measured at a 72-hour interval was max. 0,2 mm (PN-D-04101:1979). Testing of compressive strength along the grain was performed in accordance with the standard PN-D-04103:1977. A sample of standardised dimensions (20 x 20 x 300 mm) was placed between two supports and loaded at mid-length. The value of break force was read accurate to 0,01 kN. Next bending strength was calculated. Statistical calculations were performed using the Statistica application. Tested traits did not have a normal distribution and for this reason non-parametric tests were used in the analyses.

RESULTS

At breast height bending strength of wood was highest and it amounted to 54,1 MPa. At the next level (SII) strength was by 3,91 MPa (7,2%) lower. At the third level (SIII) it was lower in relation to SII by another 4,17 MPa (8,3%). At the next levels a decrease by 4,60 MPa (10%) and 2,81 MPa (6,8%) was observed in BS values. Between the butt end section (SI) and the tree top section (SV) the BS value decreased by 15,48 MPa. Median values were very similar to the arithmetic mean, which indicates that this result was not influenced by samples with extremely high or low strength (tab. 2)

Tab. 2 Statistical characteristics of bending strength of pine wood in sections

section	average [MPa]	n	standard deviation	min	max	Q25	mediana	Q75
SI ($d_{1,3}$)	54,10	552	10,41	22,50	91,91	47,94	54,30	59,93
SII	50,19	491	9,86	24,29	77,28	43,54	50,36	57,21
SIII	46,02	403	8,38	20,92	75,53	40,45	45,76	51,75
SIV	41,42	313	7,28	15,57	68,01	36,12	41,24	46,27
SV	38,61	169	7,97	22,75	79,70	33,53	37,98	43,58

Dependencies are observed between BS values determined at different heights on the trunk. Linear correlation coefficients (r) are high and the dependencies are particularly strong between values from adjacent sections. An increase in the distance between correlated sections causes a marked reduction in the strength of the relationship. This is particularly evident in the breast height–tree top relationship. Linear correlation coefficient characterising the relationship between BS at breast height (SI) and BS at the tree top (SV) is almost by 1/2 lower than the coefficient characterising the relationship of sections I and II (tab. 3).

Tab. 3 Linear correlation coefficients (r) between values of wood bending strength determined at different heights of the trunk in Scots pine

section	SI	SII	SIII	SIV	SV
SI ($d_{1,3}$)	---				
SII	**0,717214**	---			
SIII	**0,622744**	**0,687500**	---		
SIV	**0,555492**	**0,641993**	**0,819364**	---	
SV	**0,421206**	**0,460211**	**0,540989**	**0,641207**	---

The value of the coefficient of determination R^2 indicates that BS at breast height (an independent variable) relatively well describes BS only at the level of section II (20% tree height). With an increase in the distance of the measurement site from breast height a marked reduction is observed in R^2 values. In the relationship of breast height–section V, i.e. the points located the most distant from each other, its value is slight, amounting to several thousandths. However, statistically significant values of the correlation coefficient indicate that there are relationships between BS at breast height and in parts of the stem located higher. Coefficients of determination inform us on the gradually decreasing role of the independent variable BS and an increasingly important role of other unidentified factors influencing BS values at a selected measurement level. On the basis of the trend lines graphically describing investigated relationships it may be stated that an increase in the BS values at breast height will be connected with an increase in strength in other parts of the stem. This increase will decrease in proportion to the increment in the distance of the measurement site from breast height (Fig. 1).

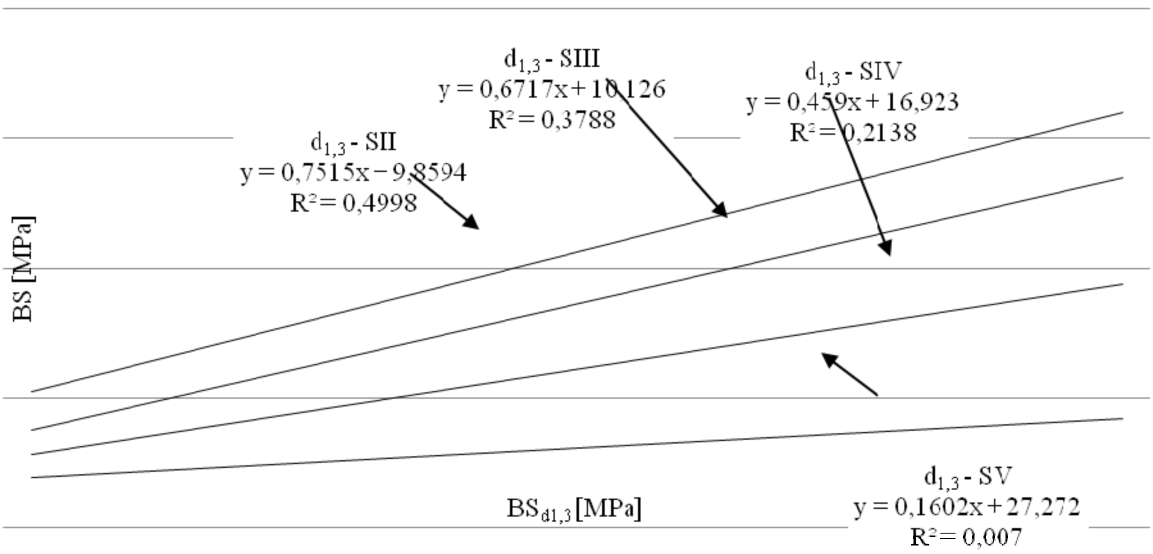

Fig. 1 Relationships between bending strength of wood at breast height and bending strength determined at different heights of the trunk

DISCUSSION

Bending strength (BS) of wood in examined Scots pines was approx. 48 MPa (at moisture content above fibre saturation point; W>30%). It is a value comparable to the results obtained e.g. by Jakubowski [2010] and Tomczak and Jelonek [2013]. It was observed that along the stem the value of the analysed property gradually decreases, from approx. 54 MPa at breast height to approx. 39 MPa at the level of section V corresponding to 80% tree height. Bending strength of wood thus exhibits variability similar to that of other properties, such as basic density and compressive strength along the grain [Tomczak et al. 2013a, b].

Bending strength of wood at breast height correlated with wood strength determined at other heights of the stem. Thus this result confirms the assumption that breast height is a representative level. Based on the results recorded for this height we may infer wood properties in other parts of the trunk. However, it needs to be stated here that the greater the distance between sections, the lower the value of linear correlation coefficient. Thus the correlation was strongest between breast height and section II (r=0,72), while between breast height and section V it was weakest (r=0,42). Wood strength in the tree top part of the stem may thus additionally correlate with other independent variables. Evidence confirming the above thesis is provided by values of obtained coefficients of determination R^2. The coefficient of determination is a measure of the percentage of variation in the dependent (explained) variable which is explained by the independent variable (predictor). In the case of breast height and section V, despite the statistically significant correlation the value of this measure does not exceed 1%.

Vestøl and Høibø [2010] correlated bending strength with different traits and properties of wood in Scots pine. The strongest and directly proportional dependence was found in relation to wood density, while it was inversely proportional in relation to the sum of diameters of knots located within 15 cm from the section. Knot sites in the trunk are potential break points of trees, particularly when they are found in verticils and are not joined with the surrounding wood [Jakubowski, Pazdrowski 2005]. Results recorded in this study were obtained from samples free from visible wood defects, including knots. Thus their effect on the obtained wood strength may be eliminated. It results from the findings reported by Vestøl and Høibø [2010] that wood density is an appropriate predictor in modeling of bending strength. Using wood strength at breast height, density and other independent variables wood strength in other parts of the stem may be estimated with a relatively good accuracy. This pertains particularly to parts most distant from breast height.

CONCLUSIONS

1. Linear dependencies, confirmed by high linear correlation coefficients, were found between bending strength at breast height and strength determined at other heights of the stem.
2. Breast height is a representative cross section of the stem. Bending strength of wood determined at this level may be used to model strength in other parts of the stem.

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Streszczenie: *Wytrzymałość na zginanie statyczne drewna sosny zwyczajnej (Pinus sylvestris L.) – związki pomiędzy wartościami określonymi na różnych wysokościach pnia.* Celem pracy było zbadanie związków jakie występują między wytrzymałością na zginanie statyczne określoną na różnych wysokościach pnia, a w szczególności między przekrojem pierśnicowym a przekrojami położonymi w innych częściach strzały. Prace terenowe wykonano w 7 dojrzałych drzewostanach sosnowych (RDLP Szczecinek). Materiał pochodził z pni 63 drzew modelowych. Z każdego pnia pobrano pięć prób, z których jedna reprezentowała poziom pierśnicy (SI), a pozostałe 20 (SII), 40 (SIII), 60 (SIII), 80% (SV) wysokości drzewa. Każdy poziom (sekcję) reprezentowały dwa przeciwległe promienie – wschodni i zachodni. Badanie wytrzymałości wykonane zostało przy wilgotności wyższej niż 30% (powyżej punktu nasycenia włókien). Wytrzymałość drewna na zginanie statyczne (BS) badanych sosen zwyczajnych w przybliżeniu wynosiła 48 MPa. Wzdłuż pnia wytrzymałość stopniowo malała. Między wytrzymałością drewna na zginanie statyczne na poziomie pierśnicy a wytrzymałością określoną na innych wysokościach pnia stwierdzono zależności prostoliniowe potwierdzone wysokimi współczynnikami korelacji liniowej. Pierśnica jest reprezentatywnym przekrojem poprzecznym pnia. Wytrzymałość drewna na zginanie statyczne określona na tym poziomie może być wykorzystana do modelowania wytrzymałości w innych częściach pnia.

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