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EFFECT OF KNOTS ON THE BENDING STRENGTH AND THE MODULUS OF ELASTICITY OF WOOD

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ABSTRACT

The utilization of wood materials is limited significantly by wood defects. This is especially valid for knots - as the most important wood defect - which can decrease the density as much as 40-50 % or in some cases even more. This is the biggest problem of the wood architecture, where the softwoods are the most commonly used materials. Hungary has shortage in good quality materials due to its forestry structure (85 % hardwoods, 15 % softwoods). This is why substituting the softwoods with hardwoods is a recurrent subject for wood industry experts. In Hungary the most important raw materials for the mass production of wooden items (boxes, pallets, board products) are the poplars. Due to its density and other physical properties they can be considered as the replacement of softwoods.

The main obstacle of utilization of poplars is the knots. The aim of this study is to examine the effect of knots on elasticity, strength and modulus of elasticity in case of hybrid poplars and softwoods.

KEYWORDS: Knot diameter ratio, bending strength, modulus of elasticity, hybrid poplar, Scots pine, SEM test of knot.

INTRODUCTION

The utilization of wood materials is limited significantly by wood defects like knots, wavy and distorted grain, etc. In terms of structural (load bearing) wood, knots are considered to be the most critical type of defect that are especially limiting the technical properties. It has the most adverse effect. Usually increasing the diameter of rough timbers has a positive effect on the quantity of good quality raw materials. But at the same time increasing the diameter of rough timbers may cause the increase of the effect of knots in quality measurements, for example in case of poplars (Danilovic 2011). Therefore, increasing knot area ratios and knot diameter ratios result in a significant decrease of bending strength (MOR) and modulus of elasticity (MOE) values. Sometimes the reduction may be as much as 40 to 50 %. In softwoods, knots of 25 and 75 mm in diameter cause 18 and 50 % decrease in bending strength, respectively (Panshin and deZeeuw 1964). The location or position of knots is an important factor in bending, sometimes more important than their size (Falk et al. 2003). Therefore there is an interest in making a survey of the position of knots nowadays as well (Que-ju et al. 2013). Similarly, expressing the effect of knots in knot area ratio (KAR) or knot diameter ratio (KDR) is also effective (Lam et al. 2005). If the projected knot area (PKA) is more than 50 %, the MOR value is about half as much as in the case of a PKA values under 20 % (Zhou and Smith 1991). Divos (1997) examined the effect of knot diameter ratio on *Picea* and *Pinus* species. In his study, the modified concentrated knot diameter ratio (CKDRm) was found to correlate well with bending strength, with a correlation coefficient of 0.608.

The anatomical structure of wood affects the strength properties of different species groups to a varying degree. The structure of ring-porous woods typically affects the technical characteristics more than that of more homogeneous softwoods (Oliver-Villanueva et al. 1996). The structure of knots differs from that of normal wood. Because knot structure varies in different species groups, the negative effect of knots is usually different in softwoods and diffuse porous species (e.g. poplars). The observations of some industrial users seem to confirm this statement.

Poplars and softwoods are important in the Hungarian forest management and wood industries. Based on some of their properties, both groups may be used in similar areas, e.g. as structural materials. The purpose of our research was to reveal the differences in the effect of knots on softwoods and poplars, and to trace the relationship between the knottiness and the strength and elastic properties by studying the material characteristics of these two species. The wood of various poplars and poplar hybrids is considered to be inferior compared to various softwoods. This depends on many factors like loose grain and low density, etc. Some poplar clones, however, exhibit reliably higher densities, in excess of 0.400 $g.cm^{-3}$. Thus, they may be considered for structural applications. The question is how knots affect the material properties as compared to softwoods.

MATERIAL AND METHODS

Because poplars are very important in Hungary (their share in the forest area and the gross harvest is 10.3 and 16 %, respectively), two clones were chosen for the investigations, namely *Populus* x *euramaricana* cv. *'I-214'* and *Populus* x *euramericana* cv. *'Pannonia'*. The density of the *'I-214'* variety is usually less than or barely over the 0.400 $g.cm^{-3}$ limit, but its significance in Hungary is such that it has to be used as control. From the softwood group, *Pinus sylvestris* L. was chosen for the study. The two poplar varieties and the Scots pine trees were harvested from similar sites to reduce the effect of external factors. The dimensions of the bending specimens were 1200x140x21 mm, which is the same as those of the top element of a pallet. The moisture content of the specimens was very high, above the fibre saturation point. Because we couldn't dry them, specimen moisture content was equalised at 45 %. The sample number was 40 for each species/varieties.

Significant correlation has been found between dynamic and static methods during modulus of elasticity measurements of wooden material which can even significantly decrease due to the knottiness (Hossein et al. 2011). The modulus of elasticity was determined using several different methods including nondestructive and destructive techniques like dynamic longitudinal vibrations, dynamic bending vibrations and static bending thanks to the development of the nondestructive methods in the past few years (Bodig and Jane 1982) and they are still continuously improving.

During the measurement of the longitudinal dynamic modulus of elasticity ($MOE_{dyn.long}$) the the vibration was induced at the end of the specimen using an impact hammer. The signal was detected by a microphone at the opposite side and analysed by a Fast Fourier Transform analyser. Eq. 1 was used for modulus of elasticity determination:

$$MOE_{dyn.long} = 4\rho L^2 f_{long}^2 \tag{1}$$

where: ρ - density,
L - specimen length,
f_{long} - longitudinal vibration frequency.

During the measurement of the dynamic bending vibration ($MOE_{dyn.bend}$) the first free bending vibration mode was used for the measurement where the length of the overhang is *0.224 l.* Vibration was induced between the supports. The signal was detected at the same location by a microphone, and evaluated by an FFT analyser. The Timoshenko theory was used for the determination of $MOE_{dyn.bend}$ because the specimens were prismatic in shape (Timoshenko and Young 1954). Since the effect of shear deformation is negligible, correction was unnecessary and the formula derived from the Euler Eq. 2 could be used:

$$MOE_{dyn.bend} = \left(\frac{f}{\gamma}\right)^2 \frac{ml^3}{I} \tag{2}$$

where: f - bending vibration frequency (mode no. 1), γ=3.561 (mode no. 1),
m - mass,
l - specimen length,
I - inertia moment.

Two methods, three- and four-point bending were used for static bending modulus of elasticity determination (EN 408: 2003). The modulus of elasticity value measured by three-point bending ($MOE_{stat.3p}$) is affected by the shear deformation between the supports. The modulus of elasticity determined by four-point bending ($MOE_{stat.4p}$) is unaffected by shear deformation, because there is no shear load between the two loading points.

Eqs. 3 and 4 were used for MOE determination in three and four-point bending, respectively:

$$MOE_{stat.3p} = \frac{\Delta F L_1^3}{48 I \Delta w} \tag{3}$$

$$MOE_{stat.4p} = \frac{\Delta F a L_1^2}{16 I \Delta w} \tag{4}$$

where: ΔF - applied load,
L_1 - span (3), and gauge length (4),
a - distance between the loading point and nearest support,
I - inertia moment,
Δw - deflection.

The determination of $MOE_{stat.3p}$ and $MOE_{stat.4p}$ allows the calculation of shear modulus as well (Eq. 5):

$$G = \frac{Kh^2}{L_1^2\left[\frac{1}{MOE_{stat.3p}} - \frac{1}{MOE_{stat.4p}}\right]} \tag{5}$$

where: K=1.2 in beams of rectangular cross section,
h - specimen depth.

Bending strength was determined by using four-point bending measurement. Eq. 6 was used for MOR calculation:

$$MOR_{4p} = \frac{3F_{\max}a}{bh^2} \tag{6}$$

where: F_{max} - ultimate load,
b - specimen width.

The effect of knots was examined according to the Japanese Agricultural Standard for Structural Softwood Lumber (JAS 1991), using the knot diameter ratio (KDR). Several methods may be used for calculating KDR, whereby the location of knots is taken into consideration. In our investigations, the knot diameter ratio was calculated on the wide face of the specimen, on the tensile side ($KDR_{wide,tensile}=d_2/b$), and in the tensile zone on the narrow face (side) of the specimen ($KDR_{edge,tensile}=d_1/h$), see Fig. 1.

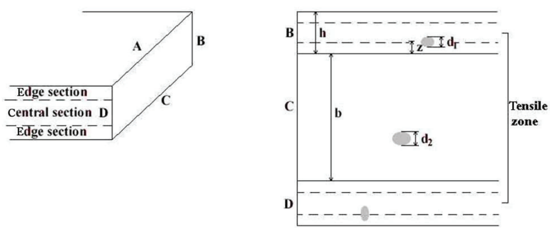

Fig. 1: The parameters used for knot diameter ratio determination.

In several cases, the knots were clustered in the specimen. The concentrated knot diameter ratio (CKDR) is used for the evaluation of the effect of clusters. An earlier study (Divos and Tanaka 1997) demonstrated the importance of the modified concentrated knot diameter ratio (CKDRm) that allows for the stress distribution in wood under load (Eq. 7).

$$CKDRm = \sum_{15\,cm\ section} KDR_{wide.tensile} + KDR_{edge.tensile}\left[1-\left(\frac{2z}{h}\right)^2\right] \tag{7}$$

Various statistical methods were used for the analysis of measurement results. Descriptive statistical parameters were calculated for the general characterisation of the measurement data series. The significance of the differences between the values of various parameters was evaluated using the analysis of variance (ANOVA). Regression analysis is most useful for detecting correlation and investigating the effect of influencing factors.

In case of knotty wood materials, practical experiences are implying that breakages are located around the knot at the edge between the knot and xylem since xylem's anatomical structure differs from knot's structure. For testing how the knot and the surrounding tissue are bonded, scanning electron microscopic pictures were taken on the margin surface of knots with different type and size.

RESULTS AND DISCUSSION

Examination of strength and elasticity properties

The investigation of the two poplar clones and Scots pine provided a conclusive result concerning the effect of knots. Tab. 1 shows the results of the statistical evaluation of the measured data. Significant correlation has been found between dynamic and static methods during modulus of elasticity measurements of wooden material (Hossein et al. 2011). On average, nondestructive MOE measurements yield higher values than the static method. The difference varies between 2-15 %. Dynamic MOE measurement results indicated significant differences between the species/clones. The '*Pannonia*' clone yielded the highest value (approx. 10 MPa), while Scots pine's values were the lowest (approx. 7.8 MPa). The results of static testing were less straightforward. The MOE of the '*I-214*' clone and Scots pine was similar, according to Duncan's test. Since there is a tight correlation between MOE and MOR, bending measurements provided similar results, i.e. the strength of knotty Scots pine (31.2 MPa) is less than that of poplars (37-38 MPa). There is no significant difference between the shear modulus of different species, although the standard deviation of the data sets is very different. The variation of the '*Pannonia*' clone is the most favourable (smallest).

Tab. 1: Statistical evaluation of the measurement data.

Species	Examined characteristics		Descriptive statistics				ANOVA[2]
			Min	Max.	Avg.[1]	Std. dev.	α
Pinus sylvestris	$MOE_{dyn.long}$	(GPa)	4.5	13.6	7.9	2.1	< 0.001
	$MOE_{dyn.bend}$	(GPa)	4.5	11.8	7.6	1.9	< 0.001
	$MOE_{stat.3p}$	(GPa)	3.9	12.8	7.5*	2.1	0.137
	$MOE_{stat.4p}$	(GPa)	4.7	13.4	7.8*	2.4	< 0.001
	MOR_{4p}	(MPa)	18.7	47.5	31.2	6.8	< 0.001
	G	(MPa)	50.1	7746.5	834.0*	1389.4	0.260
'*Pannonia*'	$MOE_{dyn.long}$	(GPa)	5.7	15.4	10.1	1.4	< 0.001
	$MOE_{dyn.bend}$	(GPa)	5.3	15.2	9.8	1.5	< 0.001
	$MOE_{stat.3p}$	(GPa)	4.0	13.1	8.4*	1.4	0.137
	$MOE_{stat.4p}$	(GPa)	4.0	21.9	10.1	3.7	< 0.001
	MOR_{4p}	(MPa)	16.0	68.1	38.4*	10.8	< 0.001
	G	(MPa)	47.4	954.5	780.4*	15.7	0.260
'*I-214*'	$MOE_{dyn.long}$	(GPa)	5.1	13.0	8.8	1.7	< 0.001
	$MOE_{dyn.bend}$	(GPa)	5.0	16.0	8.9	2.0	< 0.001
	$MOE_{stat.3p}$	(GPa)	3.7	13.8	8.0*	1.8	0.137
	$MOE_{stat.4p}$	(GPa)	5.6	15.4	8.6*	2.0	< 0.001
	MOR_{4p}	(MPa)	16.5	69.8	37.8*	9.1	< 0.001
	G	(MPa)	36.5	4929.1	584.6*	846.3	0.260

1 Results of Duncan's test. Homogeneous groups are marked by asterisks

2 One-way ANOVA comparisons of the species/varieties based on the given parameter. There is a significant difference between the species if $\alpha < 0.05$.

Several factors influence bending strength. Johansson and Kliger (2002) found that the largest influence on bending strength were modulus of elasticity, knot area ratio and grain angle. Two of these factors, MOE and knots, were investigated experimentally. The best predictor of lumber strenght is the MOE (Divos and Tanaka 1997). The effect of the modulus of elasticity determined by various methods and that of other influencing factors is best described by the correlation coefficient (Tab. 2).

Tab. 2: Correlation coefficients of the factors influencing bending strength.

Predictor	Bending strength		
	Pinus sylvestris	***'Pannonia'***	***'I-214'***
$MOE_{dyn.long}$	0.658	0.715	0.809
$MOE_{dyn.bend}$	0.672	0.736	0.806
$MOE_{stat.3p}$	0.645	0.708	0.714
$MOE_{stat.4p}$	0.672	0.732	0.753
$KDR_{wide.tensile}$	-0.532	-0.188	-0.596
$KDR_{edge.tensile}$	-0.716	-0.117	-0.432
CKDRm	-0.142	-0.201	-0.402

There is evidently a close relationship between the modulus of elasticity and bending strength. The nondestructively determined MOE values provided the best results. Fig. 2 shows the relationship between the modulus of elasticity measured by dynamic bending vibrations ($MOE_{dyn.bend}$) and bending strength. The relationship is tighter for the two poplar varieties than in the case of Scots pine.

Linear regression was used for the assessment of the effect of knots as well (Tab. 2). The correlation coefficients show clearly that the modified concentrated knot diameter ratio did not provide good results. On the other hand, the other two diameter ratios, $KDR_{wide.tensile}$ and $KDR_{edge.tensile}$ correlated well with bending strength. The location or position of knots is an important factor in bending (Falk et al. 2003). The strength reduction resulting from knots running out to the face is significant (Fig. 3). The '*Pannonia*' variety, where the correlation coefficient indicates a poor relationship, is an exception. This holds true for the other two knot diameter ratios as well. This indicates that the overall effect of knots on the '*Pannonia*' clone is not very substantial. The $KDR_{edge.tensile}$ parameter provided an especially interesting result. Knots running to the edge in the tensile zone decrease the bending strength significantly.

The examination of the effect of knots was extended to the modulus of elasticity and rigidity as well. Based on the correlation coefficients, neither knot diameter ratio has any notable effect on either mechanical parameter of '*Pannonia*' poplar (Fig. 4). The correlation coefficient for bending strength and for static modulus of elasticity is approx 0.1-0.2, i.e. the correlation is negligible. Although the coefficient is somewhat higher for the relationship of the dynamic MOE and $KDR_{wide.tensile}$, its value (0.3-0.35) is still rather low. On the other hand, the correlation coefficients indicate a tighter relationship in the case of the '*I-214*' variety, which shows that this clone is more sensitive to the presence of knots (Fig. 5). For the various moduli of elasticity, the correlation coefficient approaches 0.4, especially in the case of the two knot diameter ratios. The effect of $KDR_{edge.tensile}$ on bending strength is significant; the correlation coefficient is close to 0.6. Knots running to the side of the specimen cause significant strength loss. The effect on the modulus of rigidity is, again, negligible.

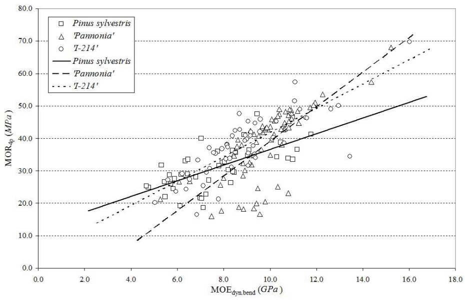

Fig. 2: The relationship between the modulus of elasticity and bending strength.

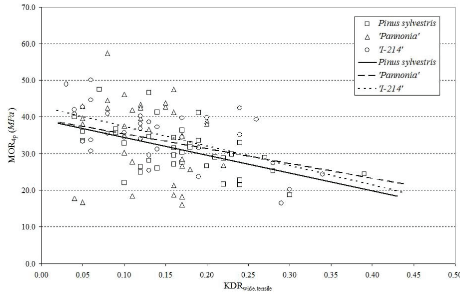

Fig. 3: The relationship between $KDR_{wide,tensile}$ and bending strength.

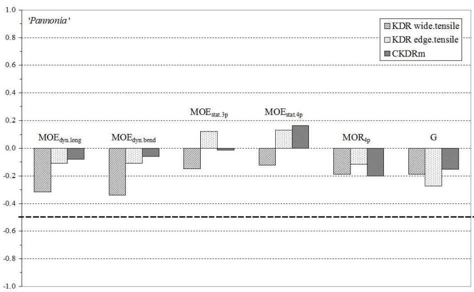

Fig. 4: The effect of knots on the various parameters of the 'Pannonia' poplar clone.

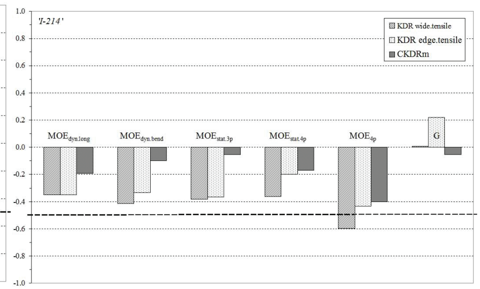

Fig. 5: The effect of knots on the various parameters of the 'I-214' poplar clone.

Based on the measurement results, the effect of knots on Scots pine is the highest of the three species and varieties examined (Fig. 6). The correlation coefficients between $KDR_{wide,tensile}$ and MOE approach and, in one case, even surpass the value of 0.4. With respect to bending strength, this value is over 0.5. The effect on shear modulus is very small again.

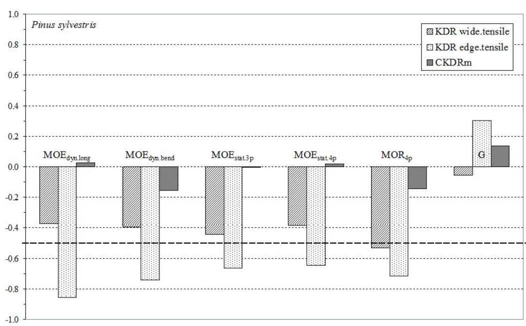

Fig. 6: The effect of knots on the various parameters of Scots pine.

The correlation between $KDR_{edge.tensile}$ and various material properties is much stronger (R = 0.65-0.85) than in the case of $KDR_{wide.tensile}$. This indicates that Scots pine's properties are very dependent on the side knots. In general, Scots pine's correlation coefficients are clearly much higher compared to the poplar varieties, especially in the case of side knots.

Examination of anatomical structure

Examination of the technical characteristics shows that different anatomical structure of the different species may have a strong influence on the strength reducing effect of knots.

The aim of the examination of the knots and the xylem around them by Scanning Electron Microscope was to give an explanation for the ruptures at the borderlines of the knots - which were detected during mechanical examination - by analysing the anatomical structure.

Considering the different types of knots it can be stated that in case of poplar wood materials less partially encased or fallen out knots may appear. Resin-ring and rough spots on the surface of the knots are frequent occurrences between the knots and the bark in softwoods (Fig. 7).

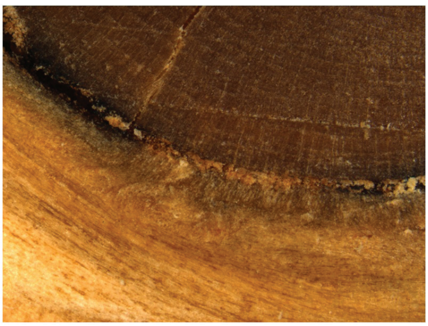

Fig. 7: Resin-ring at the borderline of the knot and the xylem (Pinus sylvestris).

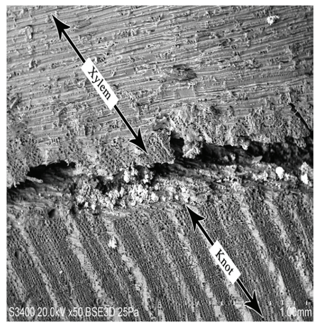

Fig. 8: The borderline between the knot and xylem (Pinus sylvestris).

According to this, stronger bond can be assumed between knots and xylem in case of poplars.

The gradation zone appears in a different way in case of poplars and Scots pine. There is a wide gradation area in the xylem around the knot in case of poplars (Fig. 9). On the other hand, in case of Scots pine the gradation zone is narrow and sharp at the borderline of knot (Fig. 8).

The examination of how knots are connected to xylem could give an explanation why Scots pine is more sensible of knottiness than poplar. In case of softwoods the narrow gradation zone between the knot and xylem, the lack of proper connection among the xylem elements is the reason of the frequent rupture around the knot. Additionally there is a huge difference between the anatomical properties (density, strength).

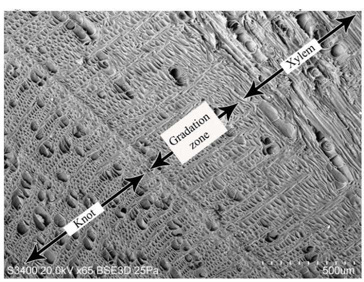

Fig. 9: The gradation zone between the knot and the xylem 'Pannonia'.

Due to the smooth gradation zone between the xylem and the knot in poplars, the two different anatomical sections join to each other along a relatively wider path. Accordingly, the negative strength reducing effect of knots is thought to be significantly decreased compared to pines.

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