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SHEAR STRENGTH AND ANALYSIS OF SHEAR AREA ON WOOD/BARK INTERFACE ON BEECH WOOD (*FAGUS SYLVATICA* L.)

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ABSTRACT

The structure of both cambium and the last-differentiated cells from cambium influence the adhesion of bark on wood. In the submitted paper, the bark/wood adhesion is evaluated by means of measuring the shear strength in longitudinal and tangential direction of the wood/bark interface on woody plant beech (*Fagus sylvatica* L.) during one year. The growing period and dormant period and moisture of the wood/bark interface proved to be important factors influencing the shear strength. The shear strength measured during the dormant period in the greenstate showed values approximately 100% higher than those measured during the growing period. Considering the 12%-moisture, the values of shear strength proved to be circa 300% higher in comparison to the green state. The shear area during the dormant period was led through the zone of the last-created sieve tubes of non-collapsed late phloem, whereas during the growing period the shear area passed through the cambium zone. The structure of shear areas is also significantly influenced by diverse structure of narrow and wide phloem rays.

KEYWORDS: Beech, shear strength, cambium, phloem, bark.

INTRODUCTION

The shear strength on wood/bark interface is closely connected with the cambial layer, which disposes of the dividing function in the living tree. The cambium centripetally creates new cells of xylem and centrifugally it creates new cells of phloem. The cambium layer, that is located as a coherent coat between increments of wood and bark, surrounds the overall tree girth (Esau 1969).

Prislan et al. (2013a) claim that the cambial layer is also involved in adjusting the outer system to the cell differentiation; this being an accompanying function apart from the essential

function of cambium, i.e. cell division. The cambium is active throughout the complete life cycle of a tree and the very differentiation of new cells takes place within the active, the growing period only Čufar et al. (2008). Cambium consists of radially flattened cambial cells with thin, non-woody primary cell walls. Prislan et al. (2013b) define the cambium zone as a radial row of highly vacuolated meristematic cells, which are responsible for creation of secondary xylem and phloem.

The structure of cambial cells considerably differs when comparing the active and dormant period. This can be observed as far as the unlike structure, number and shape of the cambial cells are concerned. By the end of the dormant period, cambium gradually gains the ability to produce new cells of xylem and phloem, following the favourable environmental conditions (temperature, moisture) (Prislan et al. 2013a). The issue of cambial activity has been depicted in a number of scientific studies (Čufar et al. 2008, Prislan et al. 2009, 2013a, 2013b, Gričar 2013, Akkemik et al. 2006, Schmitt et al. 2004, Larson 1994, Ferrrar and Evert 1997). These authors predominantly focused on factors influencing the cambial activity and even the cell division itself in diverse woody plants (pine, birch, oak, beech and maple). The above listed authors demonstrated that the cambial activity is influenced by several factors. The soil moisture, temperature and bark thickness belong to the most significant ones. Čufar et al. (2008) discovered that during the dormant season, the cambium of common beech (*Fagus sylvatica* L.) only contains 30 up to 50 % of cells as when compared to the growing season. During the active, growing season, the cambial zone significantly enlarges and subsequently, after finishing the cambial activity, it returns to the original number of cells before reactivation. Prislan et al. (2013b) analysed the production of cambial cells in dependence on altitude above sea level. Their research showed that at higher altitudes the cambial activity starts later and finishes earlier than at lower altitudes.

The living part of bark is the youngest phloem increment, this being built in period of active division of cambial cells. According to Kryczko et al. (1981), phloem represents circa 90% of the overall thickness of beech bark. The transpiration flow is limited to the non-collapsed part of phloem only. In this part of phloem, it is possible to observe, just as in wood, the zone of both early and late phloem. To a great extent, the early part of phloem is created by early sieve tubes, whose lumen in beech reaches the diameter of 52.8 ± 2.8 μm. On the other hand, the sieve tubes of late phloem, which are separated from the early phloem through a tangential layer of axial parenchyma, are approximately twice as narrow as the early sieve tubes (30.1 ± 1.9 μm). The early sieve tubes in the beech bark collapse at the end of the growing period, the sieve tubes of the late phloem maintain their function during the following dormant season, as well (Prislan et al. 2012). As the sieve tubes lose their turgor, they cease to conduct, collapse and die. However, the surrounding axial parenchymal cells remain alive much longer (they live in collapsed phloem many years) and undergo several phases of secondary changes, which lead to the development of various types of new modified cells, such as sclereids (Trockenbrodt 1990). Prislan et al. (2012) measured the diameter (18.6 μm), length (60.1 μm) and cell wall thickness (5.4 μm) of the axial parenchymal cells. Secondary changes in older phloem of beech were characterised by the collapse of sieve tubes, inflation of axial parenchyma and development of sclereides. The beech phloem does not contain phloem fibres (Holdhyde 1951). The tissue sclerification is connected with the dilatation growth of non-conducting phloem. In the non-collapsed phloem and in the first yearly increments of collapsed phloem, in principle there are no sclereids present. Sclereids are mostly found in the collapsed phloem, in vicinity to periderm (Prislan et al. 2012).

The phloem rays separate the axial phloem tissues from each other. There are essential morphological and functional differences between the "narrow", i.e. 1-8 rows, rays and the "wide", i.e. 9 and more rows, rays. The narrow phloem rays are in contact with the axial phloem tissues,

they are radially wavy as a consequence of the radial collapse of sieve tubes. On contrary, wide phloem rays are straight, they maintain their shape even after the collapse of sieve tubes. Towards periderm, they expand as a cosequence of dilatation, sclerification and storing of crystals into the rays (Kučera et al. 1980). The sclerification occurs firstly within the widest rays in their inner, central zone. The sclerification gradually proceeds to the ray periphery and the ray takes form of a wedge. The sclerotic wedge of the phloem ray usually extends even to the wooden part, whereby cambium takes form of the letter V, when viewed in the cross-section (Holdhyde 1951, Whidmore 1963, Kučera et al. 1980).

The cambial structure as described above is significantly related to the bark adhesion on wood; this being evaluated through the shear strength. Following a number of scientific works (Einspahr et al. 1971, Harder et al. 1977, Fiscus et al. 1982, Chow and Obermajer 2004), the shear strength on the wood/bark interface distinctly differs as far as the particular woody plantsare concerned. However, it also differs between the cambial activity periods, during the dormant and growing period.

The goal of the submitted paper is as follows: both to assess the bark adhesion on beech wood by specifying the shear strength on wood/bark interface and to evaluate the shear area as far as its localisation throughout the dormant and growing season is concerned. The shear strength is evaluated in terms of loading in the longitudinal and tangential direction, in terms of moisture reflecting the green state of wood and bark and in terms of moisture reflecting the equilibrium state, φ - 65%, t – 20°C.

MATERIAL AND METHODS

Beech wood (*Fagus sylvatica* L.) was used for experimental measurements. Samples were chosen from beech trees with the diameter of approximately 40 cm that grew in the research area Včelien. This area belongs to the University Forest Enterprise of the Technical University in Zvolen and is located at the altitude of about 450 m. a. s. l. in the Kremnica Mountains. The research area was characterised as a mixed forest of hornbeam, oak and beech trees. Samples, 50 mm thick, were taken from three tree trunks at the diameter of breast height, in monthly intervals from July 2015 to June 2016. Subsequently, green samples were cut into test specimens with dimensions of 30×30×60 mm ($l \times t \times r$). Afterwards, bark surfaces were cut into two identical areas with dimensions of about 30×13 mm (Fig. 1).

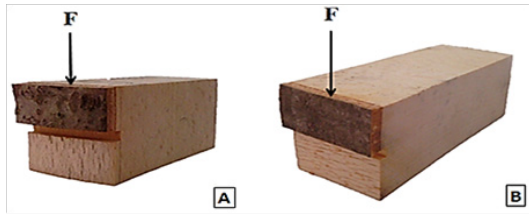

Fig. 1: Test samples for longitudinal (A) and tangential (B) testing of shear strength on the wood/bark interface.

Then, shear strength was measured in green and dry state on thus created areas. Shear strength was measured in the tangential and longitudinal direction. The dry state of specimens was reached by their conditioning at temperature of 20°C and relative humidity of air 65 %,

which corresponded with equilibrium moisture content of specimen about 12 %. The 250 tests specimen were measured approximately in green state and approximately 250 tests specimens in dry state, in total.

The adhesion testing on the wood/bark interface was performed on the testing device *TIRATEST*. Specimens were fixed with anchoring screws. The loading arm of the testing device was equipped with a special thorn, whose shape copied the wood/bark interface (Fig. 2). Stress-strain diagram was recorded from every specimen, from which maximal loading force, needed to rupture the wood/bark interface, was determined. The maximal shear strength value in the longitudinal and tangential direction in both green and dry state was calculated using the following Eq. 1:

$$\tau_{t/l} = \frac{F}{S} \quad \text{(MPa)} \tag{1}$$

where: $\tau_{t,l}$ - limit of shear strength in the tangential and longitudinal direction (MPa)
F - maximum loading force (N),
S - shear area (mm^2)

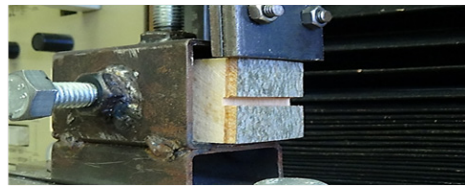

Fig. 2: Test specimen anchored by screws and by jaw edges on different wood/bark interfaces.

The taking of sample materials for analysing the cambial activity in the dormant and growing season was carried out by means of the testing device TREPHOR (Rossi et al. 2006). The samples were fixed in the FAA solution and processed into permanent microscopic preparations. The microscopic sections, approximately 10 μm thick, were coloured in the mixture of Safranin and Astra blue (Schmittz 2007).

To examine the changes on wood-cambium-phloem interface the transmission light microscope AXIO Lab A1 Zeiss and the scanning electron microscope TESCAN VEGA 5130 were used.

RESULTS AND DISCUSSION

The behaviour of the average measured values of shear strength in the longitudinal and tangential direction, measured at two moisture levels is depicted in Fig. 3 and Fig. 4. The adhesion on the wood/bark interface in both load directions is significantly influenced mainly by the structure of cambial zone and moisture of wood and bark. In the green state, in the longitudinal load direction, when the moisture in wood, cambium and bark was at a high level, the shear strength ranged from 0.68 to 0.90 MPa in the dormant period and in the growing period (May – July) it ranged from 0.39 to 0.54 MPa (Fig. 3).After drying the test specimens, when the moisture value reached 12%, the shear strength in the dormant period increased to 1.90 – 2.46 MPa and in the growing period it increased to 0.98 – 1.14 MPa (Fig. 4). When comparing the shear strength in the growing and dormant period, we can see the rise of shear

strength in the dormant period by ca. 100% on both moisture levels in comparison to the growing season.

When loading the bark/wood interface in the tangential direction, the tissues of wood, cambium and bark are stressed and subject to the traverse shear strength. The shear strength values measured in the particular months of the dormant period range from 0.58 to 0.82 MPa. During the months of growing period (May – July), the shear strength values ranged from 0.39 to 0.44 MPa (Fig. 3A), which represents the decrease of shear strength by almost a half (Fig. 4).

After re-drying the test specimens to the equilibrium moisture of ca. 12%, the shear strength on the wood/bark interface - when measured in the longitudinal direction and compared to the green state - increased more than triple the figure in the dormant period and doubly as far as growing season concerned (Fig. 3B). The shear strength values in the dry state, when loaded in the tangential direction, are approximately 2.5-times higher as when compared to the green state.

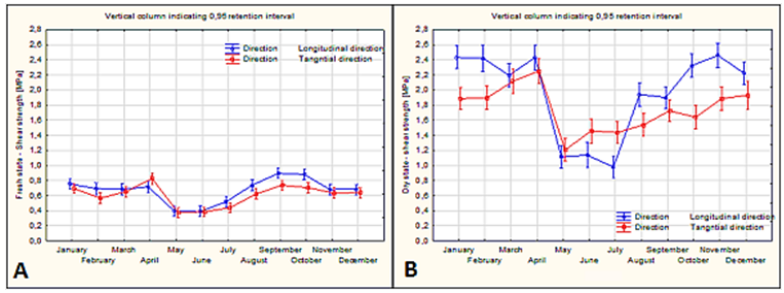

Fig. 3: Shear strength in the green (A) and dry (B) state measured in the course of one year.

As far as debarking is concerned, it is important to know the rupture zone on the wood/bark interface. Fig. 4 shows how the rupture zone is led when the shear load in the longitudinal or in tangential direction is used. When loading the wood/bark interface in the longitudinal direction, the shear zone in the dormant period is led primarily in the phloem zone (Fig. 6A). The microscopic SEM analysis proved, that the rupture zone passed through the sieve tubes of late phloem (Fig. 5A).

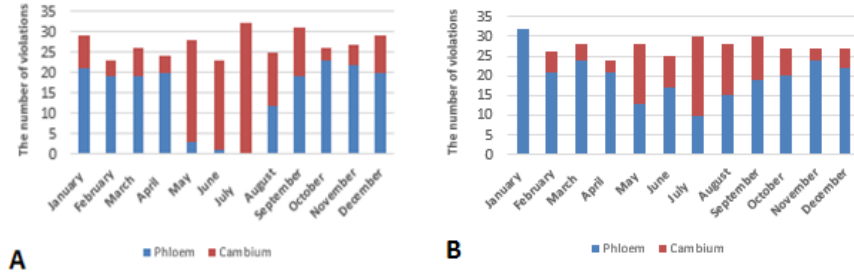

Fig. 4: Rupture zone on the wood/bark interface under longitudinal (A) and tangential (B) shear load.

In the growing period, the shear rupture zone passed mainly through the wide cambial zone (Fig. 5B, Fig. 6B). The difference in localising the shear rupture of the structure on the wood/bark interface can be ascribed to the changing quality and quantity of the cambial zone. During the growing period, the cambial zone is built by thin-walled cambial initials. The cytoplasm

usually contains one big vacuole (Čufar et al. 2008). In the dormant period, the central vacuole falls apart into a number of small vacuoles, the viscosity of cytoplasm increases and the cell walls of cambium thicken (Ferrar and Evert 1997, Prislan et al. 2013). Therefore, in the dormant period, the shear zone is shifted from the cambial zone into the zone of most recently created late phloem. The late phloem is created by thin-walled late sieve tubes and the thin-walled parenchyma. View of the shear area passing throughout the late phloem is shown in Fig. 5A. The zone of late sieve tubes that are crossed by the shear area is built by fragments of torn thin cell walls. In the growing period, which in the given year lasted from the middle of April to the middle of August, the shear area was led through the cambial zone (Fig. 5B). The cambial cells do not tear in the cell walls, they rather separate in the shear plane in the middle lamella. That is why the abrasiveness of the shear area during the growing season is lower than the abrasiveness of the shear area measured during the dormant season.

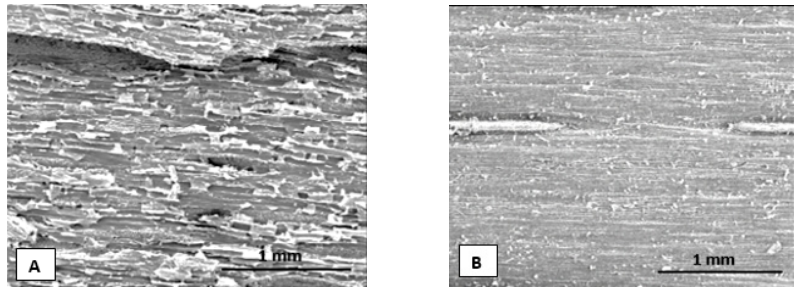

Fig. 5: Shear area led through the zone of the late phloem (A) and through the zone of cambium (B).

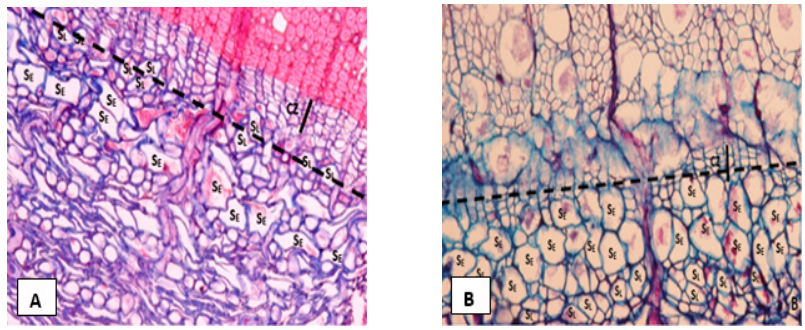

Fig. 6: Rupture zone on the wood/bark interface during the dormant (A) and the growing (B) period. CZ – cambial zone, SE –early sieve tubes, SL- late sieve tubes, --- rupture zone.

Mechanical properties of beech bark are mainly influenced by sclerenchyma tissues. There are only sclereids in the beech bark, the beech bark does not contain phloem fibres (Holdhide 1951 Prislan et al. 2012, Kučera et al. 1980). The rate of sclereids in phloem rises from cambium to periderm. There are up to 5% of sclereids in the youngest phloem, the oldest phloem parts contain as much as 35% of sclereids. There are no sclereids in the non-collpased zone of early and late phloem (Prislan et al. 2012).

Phloem rays influence the shear strength on the wood/bark interface in a very interesting way. As far as beech is concerned, two types of rays occur both in wood and phloem: narrow rays composed of 1 – 8 rows of thin-walled parenchymal cells and wide rays composed of approximately 9 and more rows (Prislan et al. 2012, Kučera et al. 1980). The wide rays have

a number of thin-walled parenchymal cell rows along their circumference and there are thick-walled sclereids perhaps even crystal-bearing parenchymal cells in the central zone (Kučera et al. 1980). Under shear load, the narrow phloem rays are transversely cut in the shear plane (Fig. 7).

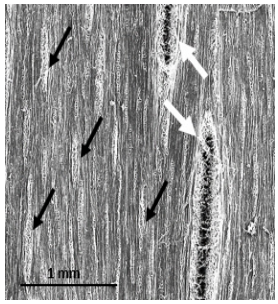

Fig. 7: Cutting of narrow (black indicator) and tearing-out of wide (white indicator) phloem rays

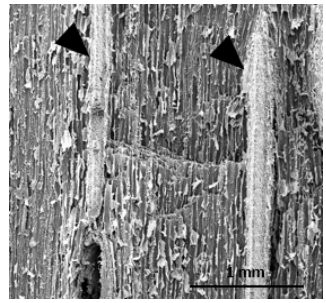

Fig. 8: Wide multi-row phloem rays in the shear plane, view from the bark side.

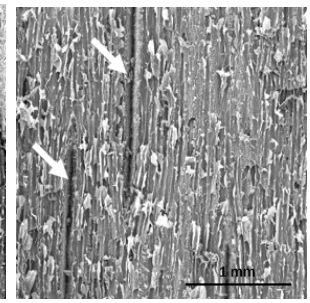

Fig. 9: Torn-out wide multi-row phloem rays in the shear plane, view from the wood.

Under shear load, the wide phloem rays are not cut in the shear plane, but they are torn out from the wood ray wedge-wise (Fig. 8). Subsequently, the wide phloem rays tower above the surface of the shear plane, which isobserved from the bark side. Observing from the wood side, wedge-shaped craters remain on the shear plane following the torn-out wide phloem rays (Fig. 9).

CONCLUSIONS

The analysis of the adhesion on wood/bark interface by means ofmeasuring the shear strength proved a significant influence of the cambial activity during the growing and dormant period. Values of shear strength during the growing period showed only ca. 30% of the shear strength value measured in the dormant period, whereas the growing period lasted from the middle of April to the middle of August. The bark and wood moisture significantly influence the adhesion of bark on wood. After conditioning the test specimens to 12%-equilibrium moisture, the shear strength increased by about 300% when compared to the green state. The shear strength is influenced by the load direction (longitudinal or tangential) to a very little extend. The rupture zone on the wood/bark interface passes through the zone of cambium under both loading directions in the growing period. In the dormant period, the rupture zone is shifted to the increment of the most recent late phloem. The multi-row phloem rays have a considerable influence on the rupture zone. These rays do not tear in the shear rupture zone, but they get wedge-wise torn out from the wood ray. The narrow phloem rays get cut in the cambial or more precisely in the phloem zone under the shear load on the wood/bark interface.

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