Int. Agrophysics, 2007, 21, 189-197

INTERNATIONAL
Agrophysics
www.ipan.lublin.pl/int-agrophysics

Analysis of the strength properties of pea stems

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Received January 3, 2006; accepted May 7, 2007

A b s t r a c t. In the study the authors determined the mechanical properties of pea stems, in the dynamic test, as well as the wall thickness of hollow stem (G) and cross-section area (S). The study was conducted on narrow-leaf pea varieties with varied resistance to lodging: Komandor (susceptible to lodging) and Brutus (resistant to lodging). For purposes of result comparison, also an older lodging-resistant variety – Piast – was included in the study. The strength characteristics of pea stems were obtained through determination of cutting work (E_d) and cutting work per unit of stem cross-section area (w_d), with the help of Dynstat apparatus. The measurements were taken at five points on the stem height. It was demonstrated that the cutting work reaches the highest value in the middle of stem length, while the work per unit of stem cross-section area is the highest close to the root. The study showed that there is a differentiation of the mechanical properties of pea stems. Varieties resistant to lodging are characterized by much higher values of their mechanical parameters. On the basis of correlation coefficients a significant correlation was found between the cutting work and the stem wall thickness and cross-section surface area. Negative correlation coefficients were obtained for the correlation between the cutting work per unit of stem cross-section area and the geometrical parameters of the stems. On the basis of the cutting work and the cutting work per unit of stem cross-section area intervarietal differences were shown. At the same time, the study in which estimation was made of the absorption of X-ray radiation by stems on the basis of the parameter ΔOD, determined with the densitometric method, showed intervarietal differences. Complementary anatomical study, made on the basis of seven traits, showed cross-sections at the analysed heights on the stems of pea varieties, suggesting also the occurrence of intervarietal differences.

K e y w o r d s: pea stem, cutting work, geometric parameters, anatomical structure

INTRODUCTION

Pea plants lodge strongly. Therefore, studies have been initiated to determine the strength characteristics of pea stems (Skubisz, 2002; Skubisz *et al*., 2004; 2005). In spite of notable success achieved in the breeding of varieties characterized by increased crop yield, breeders have been striving to obtain a variety resistant to lodging (Boros and Sawicki, 1997; Święcicki and Wiatr, 2001). As it is known, the resistance of plants to lodging is closely related to the mechanical properties of their stems (Skubisz, 1982; 2001).

In spite of the passage of time (Doliński, 1995; Jeżowski, 1981, 1996; Pickett *et al*., 1969; Skubisz, 1982), efforts are still continued in the search for and improvement of a method for the estimation of stem and root lodging, especially with respect to cereal stalks (Berry *et al*., 2003a). Those efforts resulted in indicating a varietal range of the moment of anchorage break (exceeding the limit of anchorage strength), of the values of the moment of stem failure, values of the moment of stem and plant base bending (Berry *et al*., 2003b). Among the methods used for the assessment of the mechanical properties of stems (rape) is the method based on absorption of X-ray radiation as determined on the basis of the parameter ΔOD determined with the densitometric method (Skubisz and Velikanov, 1994; 2000).

In this study the mechanical parameters of the stems of pea cultivars were determined in the process of shearing. Assessment was made of the analysed parameters of stems of narrow-leaf pea cultivars with varied resistance to lodging: Komandor (susceptible to lodging) and Brutus

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(resistant to lodging). Also, the variability of those parameters on the stem length was analysed. Moreover, the stem wall thickness and cross-section area and the value of ΔOD were determined, and the anatomy of cross-section at the particular heights on the stem was shown.

The objective of the study was estimation of the mechanical properties of pea stems and of X-ray radiation absorption by stems of pea varieties with various resistance to lodging, taking into consideration the suggestion concerning the anatomy of stem cross-sections at the analysed heights.

MATERIAL AND METHOD

The mechanical properties of pea stems were expressed by means of the cutting work (E_d) and cutting work per unit of stem cross-section area (w_d) determined in the dynamic test (Skubisz, 2001; Skubisz *et al*., 1989). The study was performed on narrow-leaf cultivars (*afila*) Komandor (lodging) and Brutus (resistant to lodging). For comparison of results, a several years older lodging resistant cultivar, Piast, was included in the study. Pea seeds originated from the collection of the Polish Bank of Pea Genes, and the plants were grown on the experimental plots of the University of Agriculture, Lublin. Plants were picked from the field at full seed ripeness. The height of plants of cv. Komandor was 72 cm, while that of plants of cv. Brutus 85 cm and of cv. Piast – 82 cm (acc. to COBORU). Representative sample consisted of 30 stems, allowing for statistical analysis of results. Strength characteristics of pea stems were obtained through the determination of dynamic cutting work and cutting work per unit of stem cross-section area, with the help of a Dynstat type apparatus.

The apparatus operates on the principle of a pendulum hammer, and for the purposes of this test the shearing knife of the apparatus travelled at the speed of $v=2.1$ m s^{-1} In this test the dynamic cut work was expressed in terms of the value of kinetic cutting energy lost by the pendulum hammer in the course of the cutting (Skubisz *et al*., 2005). At the same time, measurements of the outer diameter (Φ_z) and inner diameter (Φ_w) were made at the point of dynamic shearing. The diameters are necessary for the determination of the stem wall thickness (G) and of the stem cross-section area (S). The diameters were measured with the help of a stem cross-section meter, the design of which is protected property of the Institute of Agrophysics Polish Acadaemy of Sciences, Lublin (Skubisz, 1982). To determine the variability of the mechanical properties on the stem length, measurements were taken at five points on stem length (at five stem heights). The first point of measurement was at the root (about 2 cm above). The stem was divided into five equal parts, from the root to the top. Measurements were made on stem sections of standard length.

In the study an X-ray radiation absorption by pea stems was determined (Skubisz and Velikanov, 1994).

The densitometric method was used to determine the value of ΔOD which indicates the degree of brightening of the film after the passage of X-ray radiation through a stem, which corresponds to the amount of radiation energy absorbed by the stem. This means that the densitometric experiments were performed to determine a number of values (specified below) which allowed for an analysis of X-ray pictures obtained after the passage of X-rays through the stems at specific measurement spots.

At the same time complementary anatomical studies were made at the measurement points on the pea stem at which the mechanical properties and X-ray radiation absorption were determined. The anatomical studies of stems were performed for Komandor, Brutus and Piast pea cultivars using light and scanning electron (JSM-35C) microscopes on the basis of the following characters: thickness of perimedullar zone (pz - zone of small-celled parenchyma surrounding the vascular bundles, with thickened cell walls), number of pz cells along the radius, number of collenchyma cell layers at stem ribs, number of collenchyma cell layers in other parts of stem, maximum wall thickness of primary phloem (pf) fibres at stem ribs, maximum wall thickness of pf fibres in other parts of stem, maximum thickness of cell walls in parenchyma cells of medullary rays. The degree of interfascicular cambium development was also evaluated. Three stems (individuals) of each cultivar were examined. Measurements were taken at the same five points on stem length, in ten replications for each character. The anatomical studies were directed, in the main, at bringing to light the qualitative intervarietal differences in stem structure – presence or absence of interfascicular cambium, developed collenchyma, peculiarities of stem architectonics in lower stem part. Measurements were reconnoitring (of searching nature) and were performed to reveal the most characteristic features affecting pea stem mechanical properties. However, the results of studies constitute but a suggestion for the evaluation of cultivars, as the insufficient number of samples does not permit statistical analysis to be performed. Nevertheless, they indicate the anatomy of the stem cross-section of the pea cultivars at the analysed points on the stem height.

RESULTS

A characteristic run of variability of the mechanical parameters was found on the stem length, as presented in Table 1 and Fig. 1.

The study showed that the cutting work and the ΔOD reach an extreme value. High values of the shearing energy are characteristic of the middle sections on the stem length. Simultaneously, the value of ΔOD for the second or third section reaches its minimum. The results are presented in Table 1 and Fig. 1. Analysis of variance for cutting work between particular measurement points showed significant

Table 1. Mean values of assignment parameters in the cutting process, X-ray radiation absorption and geometric parameters of pea cv. Komandor, Brutus, and Piast stems during full podding (x – average , W – coefficient of variability)

Measurement points on the length	Statistical parameter	Assignment parameters				
		E_d (J)	$w_d x10^{-2}$ (J mm^{-2})	G (mm)	S (mm^2)	ΔOD
		Phenological phase – full podding				
		Komandor				
1	x	0.18	3.36	0.64	5.43	0.31
	W	19	29	20	34	22
2	x	0.20	2.52	0.66	7.78	0.28
	W	18	28	20	29	13
3	x	0.20	2.31	0.66	8.54	0.27
	W	19	29	21	31	26
4	x	0.18	2.15	0.66	8.46	0.28
	W	23	25	20	29	28
5	x	0.16	2.65	0.60	5.92	0.34
	W	19	33	17	24	12
		Brutus				
1	x	0.22	3.72	0.67	5.86	0.43
	W	25	26	27	36	28
2	x	0.27	2.52	0.84	10.83	0.36
	W	20	21	16	21	18
3	x	0.31	2.44	0.85	12.77	0.37
	W	19	25	17	23	15
4	x	0.26	2.19	0.77	12.05	0.39
	W	21	22	19	25	18
5	x	0.25	2.37	0.73	8.54	0.45
	W	13	28	19	26	30
		Piast				
1	x	0.21	3.45	0.63	6.22	0.42
	W	28	27	24	34	20
2	x	0.27	2.50	0.82	10.64	0.33
	W	24	22	20	46	18
3	x	0.28	2.31	0.81	12.27	0.42
	W	23	27	13	55	20
4	x	0.28	2.38	0.82	11.81	0.44
	W	27	23	19	46	19
5	x	0.21	2.06	0.71	10.18	0.43
	W	21	34	20	35	24

differences for the Brutus cultivar. Homogeneous groups can be observed that have no significant differences – for the Piast cultivar they are stem sections number two, three and four, and for the Komandor cultivar, sections two and three. The study showed that the cutting work was correlated with the geometric parameters and the value ΔOD of the stems. Positive correlation was found for this parameter with the stem wall thickness and cross-section area, while $r_{0.05}$= 0.1319 ($E_d \times G$ = 0.4645 for Komandor, 0.3434 for Brutus, and 0.4386 for Piast: $Ed \times S$ = 0.5493 for Komandor, 0.5395 for Brutus, and 0.4163 for Piast). Cutting work per unit of stem cross-section area reached the highest values close to the root. Analysis of variance performed for the particular measurement points on the stem length showed significance of differences between the root and top sections of the stem and the middle sections, while measurement points number two, three and four constituted homogeneous groups with no significant differences. The same conclusion was arrived at for the value of ΔOD attained for the Komandor and the Brutus cultivar. Significant correlation coefficients were observed – negative correlation between the mechanical parameter under study and the geometric parameters and also for the value ΔOD for cultivars resistant to lodging (Brutus and Piast): $w_d \times G$ = -0.5570 for Komandor,

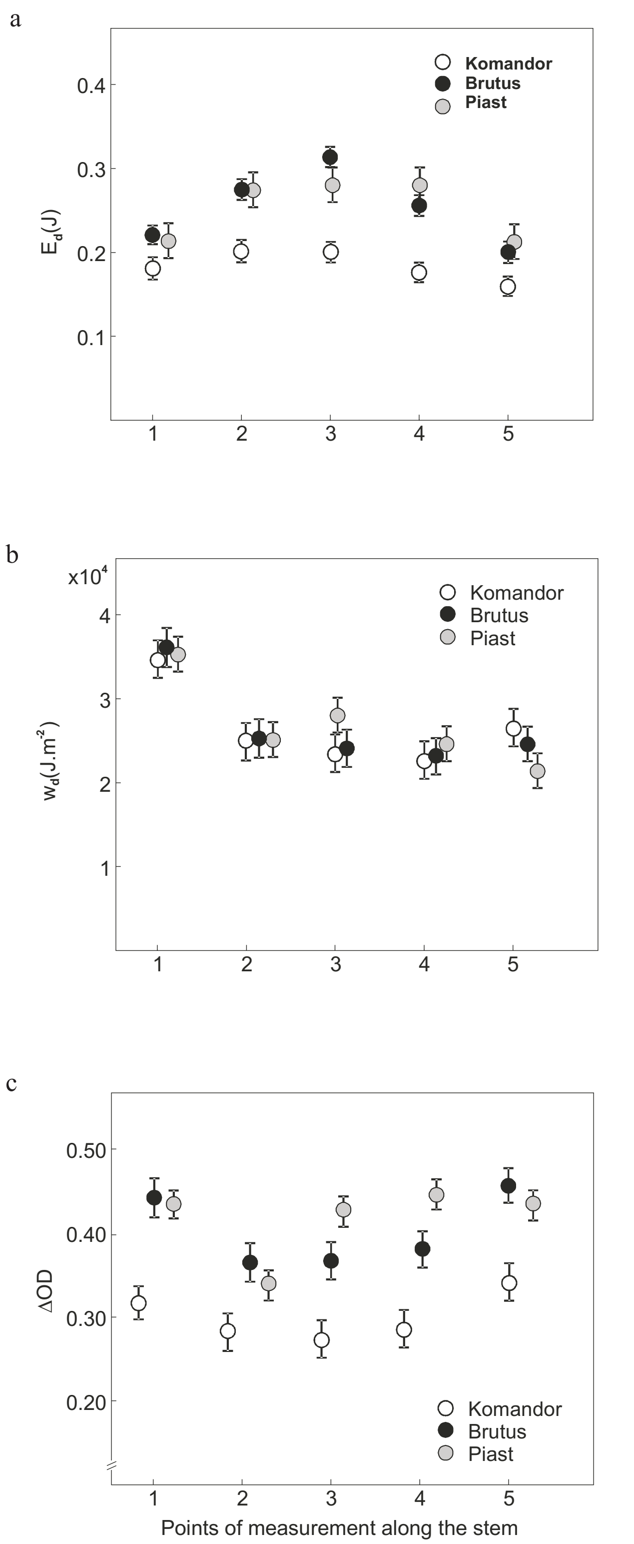

Fig. 1. Mean values and 95% Tukey HSD intervals: a – of the cutting work (E_d), b – of the cutting work per stem total cross-section area (w_d), and c – of the value of ΔOD; for experimental points on the length of pea stems (1..5 points on the length of stems from the root to the tip, for complete pod filling and full ripeness).

-0.6976 for Brutus, and -0.3250 for Piast; $w_d \times S$ = -0.7297 for Komandor, -0.7200 for Brutus, and -0.7867 for Piast and $w_d \times \Delta OD$ = -0.3227 for Brutus, -0.4734 for Piast. The complementary anatomical studies of stems of three pea cultivars - Komandor, Brutus and Piast – at the particular points on the stem length (from the base to the top of the plant) permitted the following observations:

– thickness of perimedullar zone (pz) – Komandor: 15-35, 16-35, 19-35, 20-35, 14-25; Brutus: 18-38, 18-36, 20-46, 22-45, 22-50; Piast: 20-34, 21-35, 19-46, 18-43, 17-30;
– number of pz cells along the radius – Komandor: 5-8, 5-8, 5-9, 6-11, 5-10; Brutus: 6-10, 5-10, 6-10, 7-12, 7-13; Piast: 6-11, 6-10, 5-9, 5-10, 5-11;
– number of collenchyma cell layers at stem ribs – Komandor: 0-2, 4-5, 3-5, 4-5, 3-6; Brutus: 3-3, 3-4, 4-5, 4-5, 5-8; Piast: 1-3, 3-5, 3-5, 3-6, 1-5;
– number of collenchyma cell layers in other parts of stem – Komandor: 0, 0, 0-1, 0-1, 0-2; Brutus: 0-2, 0, 0-2, 0-1, 0-1; Piast: 0, 0, 0-1, 0-4, 0-3;
– maximum wall thickness of primary phloem (pf) fibres at stem ribs – Komandor: 2, 1.5, 2, 2.5, 2.5; Brutus: 3, 2, 3, 2.5, 3; Piast: 4, 5, 5, 4, 6;
– maximum wall thickness of pf fibres in other parts of stem – Komandor: 3, 2, 1.7, 4, 3; Brutus: 3.5, 3.5, 5, 5; Piast: 5, 5, 4, 5, 5;
– maximum thickness of cell walls in parenchyma cells of medullary rays - Komandor: 2.5, 1.5, 1.5, 1.5, 4; Brutus: 2.5, 2, 7, 8, 7; Piast: 4.5, 4, 3.5, 3, 4.5.

Pea stem – hollow (Fig. 2), slightly ribbed, lesser at upper part, roughly quadrate in section, conducting system retains bundle-type structure. Vascular bundles are collateral, those arranged along the stem ribs differ from the other bundles by smaller vessel diameter and well developed outer strand of sclerenchyma, consisting of primary phloem fibres. Over them there is collenchyma (up to 8 layers of cells), poorly developed or absent in other stem parts. Close to the stem top the stem edges are less developed and the differences between the vascular bundles are less pronounced.

The reported earlier (Skubisz *et al*., 2004) smaller stem thickness in the Komandor cultivar corresponds to the smaller width of the perimedullar zone of the stems of this cultivar and can be attributed to the weaker secondary growth of the stem; interfascicular cambium, which ensures stem thickening, lacks, at least at measurement heights Nos 2-5, whereas in two other cultivars studied it is visible in the stem, the most developed being in Brutus cultivar (Fig. 3).

In the stems of all the cultivars there is a thickening of cell walls in parenchyma cells of medullary rays that is due to the appearance of an inner soft cell wall layer. It is seen at different stem levels in the cultivars: near the top (stem section No. 5) in Komandor cultivar, in the middle and upper stem parts (stem sections Nos 3-5) in Brutus cultivar, and 1-2 levels lower in Piast cultivar. The wall thickness of those cells is the least in the Komandor cultivar and the largest in

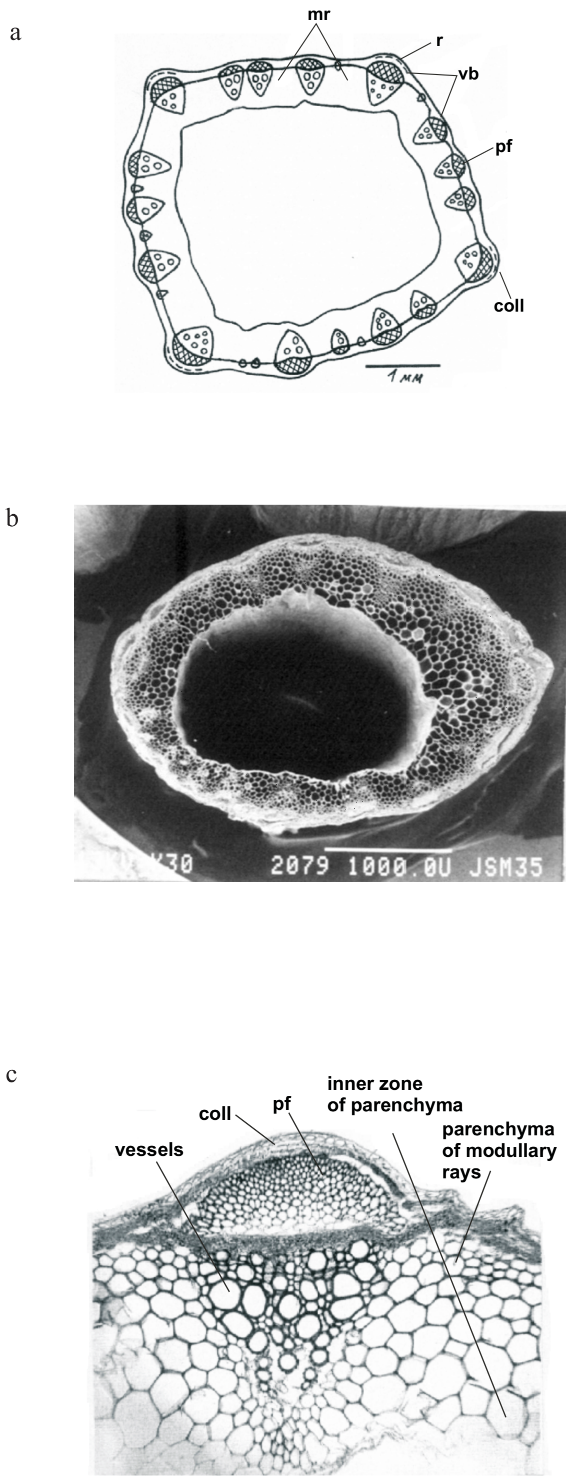

Fig. 2. Anatomy of the pea stem: a) coll – collenchyma, mr – medullary rays, pf – primary phloem fibers, r – stem ribs, vb – vascular bundles (for the Komandor cultivar/2 – 2nd experimental point on the stem); b), c) for the Komandor cultivar /5.

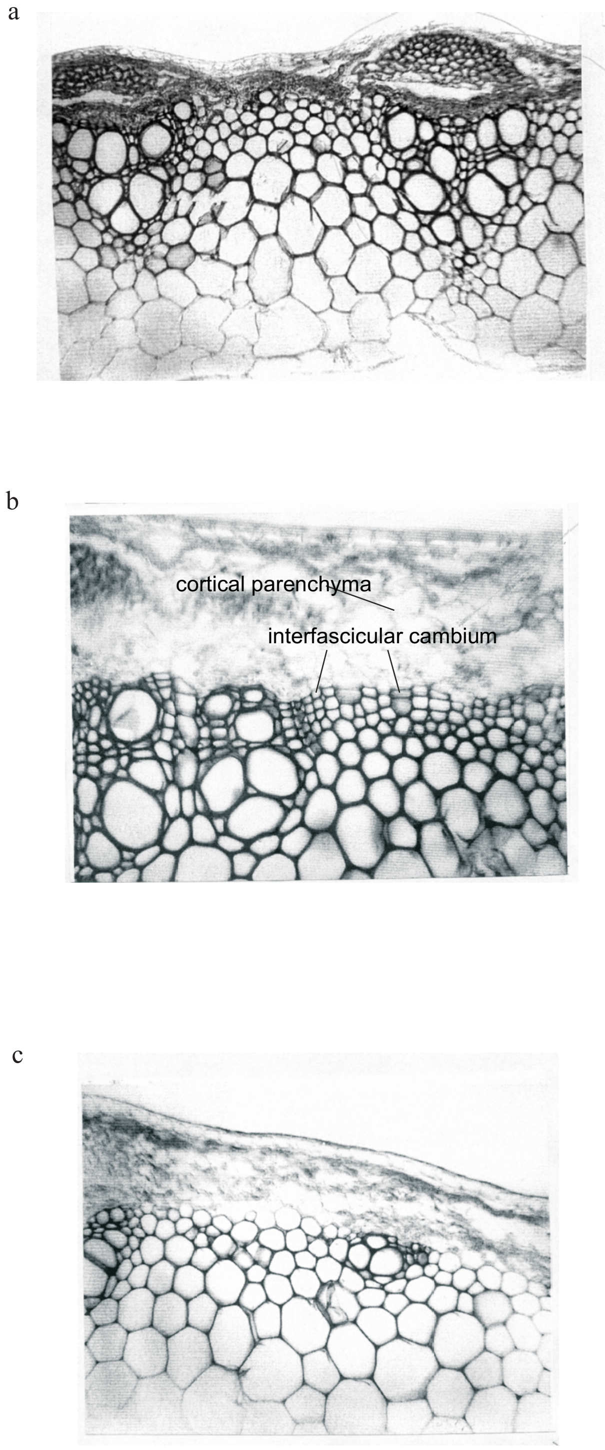

Fig. 3. Anatomy of the pea stems for the a, b – Brutus cultivar/2, and c – Komandor cultivar/2. Explanations as in Fig. 2.

the Brutus cultivar (Fig. 4). Moreover, the Komandor cultivar differs from the other cultivars by smallest thickness of primary phloem fiber walls (Figs 5 and 6).

The analysis of anatomical structure of the pea stem permits to suppose that the tendency of pea stems to lodging is determined mainly by some peculiarities of it structure close to the root (stem section No. 1): in the Komandor cultivar there is relatively low development of the collenchyma lower stem part (0-2 cell layers in the stem ribs as compared to 3-4 or 1-3 in the Brutus and Piast cultivars); the innermost zone of large-celled parenchyma (the rest of stem pith), which is weak mechanically as compared with neighbour more hard small-celled tissues, at this stem level is continuous in Komandor cultivar and occupies a sizeable part of section surface, whereas in other cultivars studied this zone is interrupted. The architectonics of stem in its lower part is hence different in lodging and resistant cultivars: in Komandor cultivar there is inner cylinder of mechanically weak tissue, whereas in two other cultivars – ribs of mechanically strong tissue jut out into this inner zone, interrupting it (shown in white in Fig. 7).

The study of the mechanical and the densitometric parameters in conjunction with the complementary anatomical studies of pea stems provided a deeper insight into the strength characteristics of the stems of the pea cultivars studied.

a

b

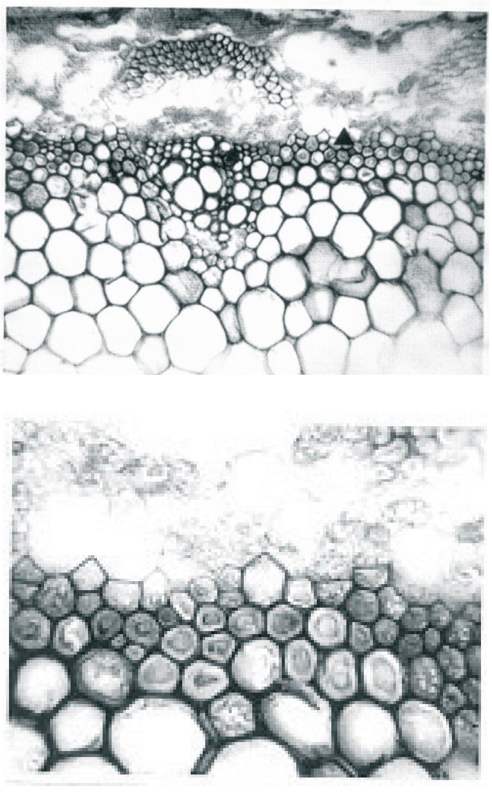

Fig. 4. Fragments of cross-section of pea stem: a – in the Brutus cultivar/4 , b – magnified 9 of 4a. Explanations as in Fig. 2.

a

b

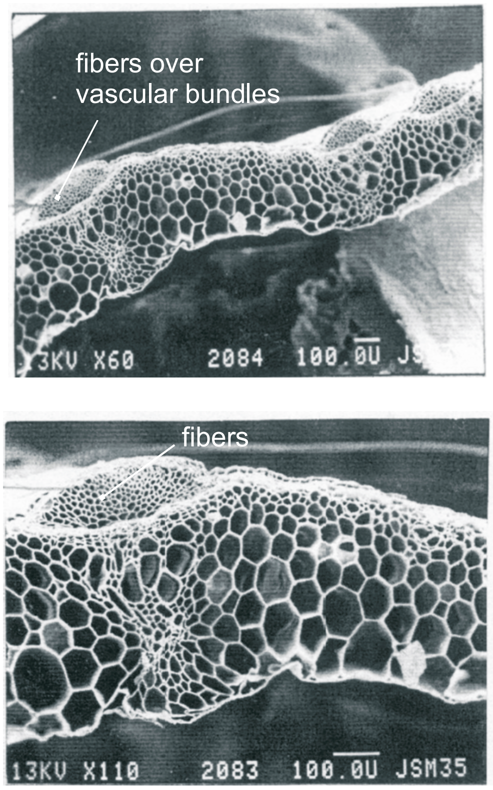

Fig. 5. Anatomy of the: a – pea stem for the Komandor cultivar/2, b – magnified 10 of 5a. Explanations as in Fig. 2.

a

b

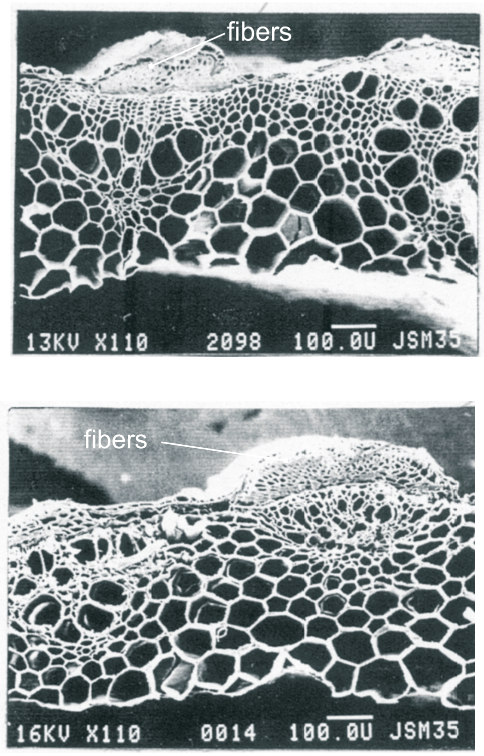

Fig. 6. Anatomy of the pea stem for the: a – Brutus cultivar/2, b – Piast cultivar/2. Explanations as in Fig. 2.

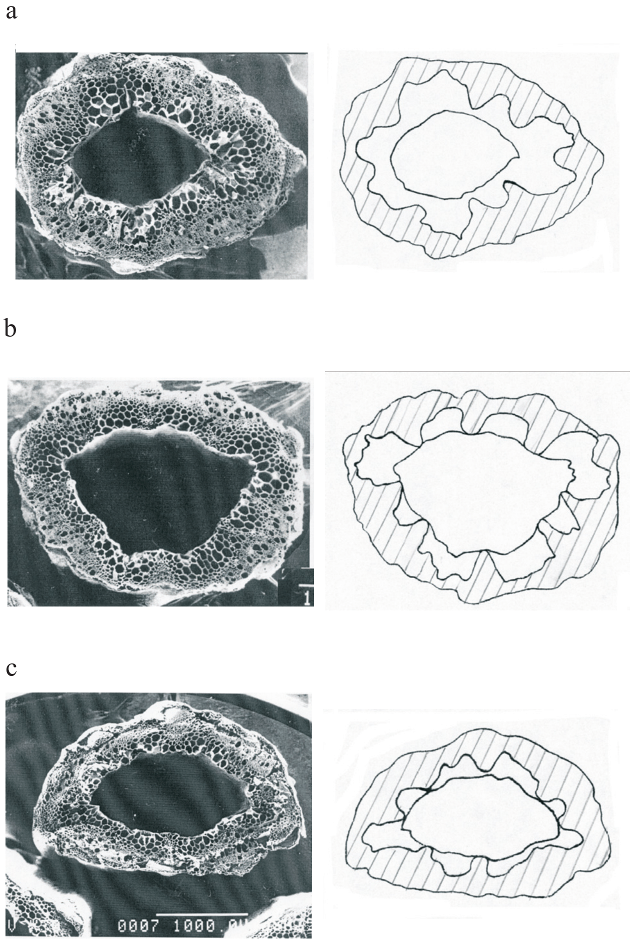

Fig. 7. Anatomy of the pea stem for the: a – Komandor cultivar/1, b – Brutus cultivar/1, and c – Piast cultivar/1, in SEM micrograph and in schematic, white – the innermost zone of large-celled parenchyma. Explanations as in Fig. 2.

DISCUSSION

The study showed significant differentiation of the strength properties on the stem length as well as differences between the cultivars. Similar observations were made in earlier studies on the Piast and Agra pea cultivars, and on the basis of characteristics from static bending test performed for the Piast, Brutus, Komandor and Rola cultivars (Skubisz, 2002; Skubisz *et al*., 2005). Reviewing the literature, Dunca (2003), Skubisz (1982), and Żuk (1994) observed variability of the mechanical properties of cereal stalks, and Speck *et al*. (1996) variability of the mechanical properties of the stems of herbaceous plants. In this study the fact that the strength characteristics of pea stems show inter-cultivar differences was confirmed by X-ray absorption tests.

Already earlier studies showed a relation between the cutting parameters and ΔOD, as well as inter-cultivar differences. However, in the case of rape stems there was a particularly strong relation (positive coefficients of correlation) between the cutting work per unit of stem cross-section area w_d and X-ray radiation absorption defined by means of the parameter ΔOD (Skubisz, 2001; Skubisz and Velikanov, 1994).

The object of studies by numerous authors who estimated the resistance of plants to lodging was the content of skeleton substances in plant stems. Ślusarczyk (1971) demonstrated, for various cereal species and cultivars, differentiation in the content of lignin, cellulose, and hemicellulose. In a study on rape stems by Skubisz (2001), a 50% lower content of lignin and 50% higher content of cellulose were found in non-lodging cultivars, while reverse proportions were characteristic of lodging cultivars. At the same time those groups of cultivars differed significantly in their content of hemicellulose.

The content of lignin has been accepted by many authors as the value responsible for the strength properties. The extent to which lignin determines the strength properties of plant stems is being analysed by numerous researchers who perceive its significant role and study the properties of lignin as an important component determining the strength properties of stems. Lignin is analysed in cell walls of woody tissues of plants (tobacco plant wood, tree wood). It was demonstrated that lignin in cell walls of tobacco plants behaves in a manner similar to the behaviour of polymer solutions (Hepworth *et al*., 1998). Also, a technology was presented for increasing the rigidity of composites of plant fibre (flax) through epoxy resin penetration into the cell walls (Hepworth *et al*., 2000). Analysis was made of the role played by microstructure in the mechanical strength of natural material with cellular structure. Studies were conducted on materials with structures resistant to local buckling (plant stems and animal tubular structures) (Karam and Gibson, 1994; Karam *et al*., 1994). A review was performed of the mechanics of a broad range materials with cellular structure, and an analysis of their role in natural lightweight layered structures *eg* iris leaf (Gibson *et al*., 1988) and tubular structures *eg* plant stems and animal tubular structures (Gibson, 2005). In the light of literature references, the strength properties of cells and tissues have been considered by numerous authors who, among other things, demonstrated the relationship between the mechanical properties and the content of cellulose (Rusin, 2002).

In a study on pea stems (Banniza *et al*., 2005), in which estimation was performed of the relationships among lodging, stem anatomy, degree of lignification, and resistance to mycosphaerella blight in field pea, it was shown that lodging was negatively correlated with proportions of supportive tissue (formerly parenchyma cell in the pith periphery, which have differentiated to sclerenchyma) and xylem in stem sections, whereas disease ratings were negatively correlated with xylem. Lignin and fibre contents in pea stems were negatively correlated with both lodging and mycosphaerella blight severity. Cellulose content was also negatively correlated with lodging scores. Indeed, the individual proportions of supportive tissue and xylem were corre- lated with lodging. A higher ratio of supportive tissue and xylem resulted in less lodging. Samarin and Samarina (1979) attributed lodging to a higher weight of the upper pea plant part compared with that of the lower plant part and a significant interaction with stem strength at internode 5-6. In the study by Banniza *et al*., (2005) the diameter of this internode was not correlated with lodging. However, based on the correlation analysis, the diameter of 2-3 internode accounted for 16% of the variability observed in lodging among the cultivars. The increase in stem diameter, of approximately 50% between internode 2-3 and internode 8-9, accounts for much of the lodging behaviour of this species. This was observed in time lapse video studies where initial stem failure occurred at the basal region of the stem, where vascular tissue is positioned in the stems centre and where the internode is the narrowest (Swinhoe *et al*., 2001). Nevertheless, rigidity was the highest in the middle of pea stems, and resistant to lodging pea cultivars had higher rigidity levels than cultivars susceptible to lodging (Skubisz, 2002; Skubisz *et al*., 2001; McPhee and Muehlbauer, 1999), contrary to the conclusion of Samarin and Samarina (1979). In the present study, both in pea stem cutting tests and on the basis of X-ray radiation absorption of cultivars resistant and susceptible to lodging, variability of strength properties on the stem length was demonstrated, as well as inter-cultivar differences. Also the complementary anatomical study confirmed the above results. It was found that the cutting work (positive coefficients of correlation) and the cutting work per unit of stem cross-section area and the parameter ΔOD (negative coefficients of correlation) were correlated with the geometry of the stems as expressed by the cross-section surface area and stem wall thickness.

CONCLUSIONS

1. The analysed pea cultivars differ in the mechanical properties of their stems.

2. Brutus, like the older lodging-resistant Piast cultivar, is characterized by much higher values of cutting work and the value of ΔOD as compared to the lodging cultivar - Komandor.

3. Pea stem cutting work reaches its maximum in the middle of stem length. Also, nearby this place, the value of ΔOD reaches its minimum. Cutting work per unit of stem cross-section area in all the cultivars has the highest values close to the root.

4. Positive correlation was observed between the cutting work and the stem wall thickness of the pea cultivars. Smaller stem wall thickness in Komandor cultivar as compared with lodging-resistant cultivars Piast and Brutus can be attributed to lower cambial activity, which is expressed by absence of interfascicular cambium in most stem part.

5. Significant differentiation was observed in the strength properties along the stem length.

6. The results obtained permit to suppose that the weak resistance to lodging in the Komandor cultivar is connected with some characters of stem structure close to the root – with low development of collenchyma and peculiarities of stem architectonics at this stem part.

7. The Komandor cultivar, as compared to Brutus and Piast, is characterized obviously by the least wall thickness of primary phloem fibres and the least wall thickness of parenchyma cell of medullary rays.

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