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STEM RESISTANCE IN TRADITIONAL AND SELF-COMPLETING FABA BEAN CULTIVAR (*Vicia faba* spp. *minor*) TO BENDING PART I. EFFECT OF THE MORPHOLOGICAL STRUCTURE OF STEMS

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Abstract. The present research investigated two faba-bean cultivars: traditional Neptun and self-completing Granit harvested from the experimental field of the Mochełek Experiment Station, the Faculty of Agriculture and Biotechnology, the University of Technology and Life Sciences, over 2008-2010. The analysis of morphological characteristics was made at two seed maturity stages: physiological and technical. The stem strength traits: stem section modulus W_y and maximum bending load σ were determined with the use of INSTRON 8874 universal testing machine (High *Wycombe*) applying 80 mm stem fragments sampled from the internode right under the first pods. The faba bean cultivars investigated, despite the lack of differences in the degree of lodging, differed significantly in terms of 5 out of 7 morphological traits researched. As for the physiological seed maturity, average stem section modulus W_y was significantly higher than at full maturity. Average maximum bending stress σ (stem resistance to bending), on the other hand, was significantly differentiated neither by the degree of seed maturity nor the faba bean cultivar. The increase in the total stem length and the setting height of the 1st pod and the length of fruit-bearing shoot, as well as the stem thickness and its inner diameter was accompanied by the increase in the stem section modulus and a decrease in stem resistance to bending.

Key words: cultivar type, faba bean, morphological traits, stem resistance to bending

INTRODUCTION

The main causes of the plant stem lodging, including legumes, is a lush vegetative growth which can result from a high total precipitation over the plant growth or the

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agronomic errors made, e.g. the application of too high nitrogen fertilisation doses, an excessively high sowing density and giving up weed control [Jasińska and Kotecki 1993]. Similarly excessive rainfall over generative development in combination with sudden weather phenomena, mostly thunderstorms and strong wind, contribute to plant lodging before harvest, especially over the years favourable to faba bean yielding and the development of a large vegetative weight and a high number of pods [Kotecki 1990]. According to COBORU, faba bean lodging is more frequent in traditional than in self-completing cultivars and it is closely connected with the plant height [Osiecka and Wiatr 2010]. The traditional cultivars also demonstrate a higher productivity than the self-completing ones, mostly thanks to a greater length of the fruit-bearing shoot and the number of nodes with pods [Księżak 2002]. Similarly in soybean, traditional cultivars (with an undetermined growth), which are high and susceptible to lodging, yield highest; the self-completing cultivars (with a determined growth), on the other hand, yield satisfactorily provided a high plant growth and high resistance of stems to lodging are ensured [Wilcox and Sediyama 1981].

Lodging provides a technical difficulty not only for harvest, and makes it more expensive, but it can also result in a considerable decrease in the seed yield, especially if it occurs over flowering. With that in mind, one of the major objectives of faba bean breeding is not only shortening the vegetation period but also the stem since both characters are positively correlated with the seed yield [Jasińska and Kotecki 1993].

The older the plants, the more changes in the physical properties of stems [Górecki *et al.* 1999]. The changes also emerge as a result of tissue moisture and they are species- and cultivar-specific and depend on the place of measurement [Chattopadhyay and Pandey 1999, Haman and Konstankiewicz 1999, Skubisz 2002, Lisowski 2010].

The working hypothesis assumes that faba bean cultivars significantly varied in terms of height and other morphological traits will differ in the degree of stem resistance to bending. The objective of the present research was to provide characteristics of stem resistance to bending in traditional and self-completing faba bean cultivar and their connection with the morphological structure.

MATERIAL AND METHODS

The present research investigated two faba bean cultivars: traditional Neptun and self-completing Granit, harvested from the experimental field of the Mochełek Experiment Station (53^{o}13’ N; 17^{o}51’ E) of the Faculty of Agriculture and Biotechnology, the University of Technology and Life Sciences, over 2008-2010. Each cultivar was sown in 33.6 m^2 plots in 4 reps; traditional cultivar Neptun assuming 70, and self-completing Granit – 90 plants per 1 m^2. Faba bean cultivation involved the use of standard agronomic practises (without N fertilisation) [Jasińska and Kotecki 1993].

For the purpose of research there were randomly sampled 4 times x 6 plants from each plot and cultivars at two development stages: at the beginning of physiological maturity and at full seed maturity. From a node fragment right under the first pod there were cut 120 mm sections, of which 80 mm were allocated to strength research, and 40 mm – for anatomy research.

The strength research was performed based on the analysis of maximum bending stresses obtained from the diagrams of four-point bending of the fragments sampled.

Stem fragments 80 mm long were positioned by marking the point of application of the bending moment, namely by orienting the position of axis y to correspond to Fig. 1.

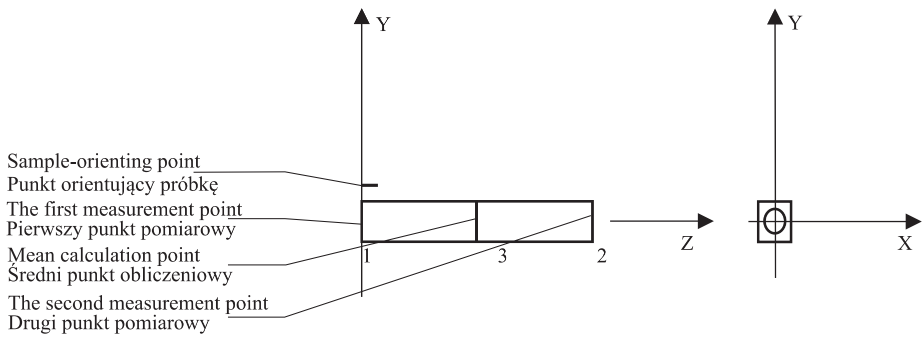

Fig. 1. Diagram of the sample with a faba bean stem and its orientation (plane y-y is the load--inflicted plane)
Rys. 1. Schemat próbki łodygi bobiku z oznaczeniem jej orientacji (płaszczyzna y-y jest płaszczyzną zadawanego obciążenia)

External stem measurements x and y towards the adequate exes were measured about 5 mm away from both ends of the samples. At the same points stem internal diameter d was measured. For each sample there were determined $x_{śr}$ and $y_{śr}$ and $d_{śr}$ as mean values measured from both ends. Treating the stem cross-section as the model of the rectangular cross-section with the measurements of $x_{śr}$ and $y_{śr}$ as well as internal diameter $d_{śr}$, there was estimated its mean cross-sectional area $F_{śr}$ and the mean value of section modulus $W_{yśr}$ according to the relationships given below [Niezgodziński and Niezgodzińska 2010]:

for cross-section:

$$F_{śr} = x_{śr} \cdot y_{śr} - \pi \cdot d_{śr}^2/4$$

for section modulus in axis y-y:

$$W_{yśr} = (J_{prostokąt} - J_{okrąg})/e \ [mm^3]$$

where respective axial moments of inertia are as follows:

$$J_{prostokąt} = x_{śr} \cdot y_{śr}^3/12$$

$$J_{okrąg} = \pi \cdot d_{śr}^4/64$$

and

$$e = y_{śr}/2$$

The stem load diagram is given in Fig. 2 where R stands for the reactions of support forces, and P stands for the inflicted load. The values of the forces of reaction and load were the same. The diagram presents also the distance relations between the supports (70 mm) and the load-inflicted points (40 mm). Such bending guarantees the stability of the bending moment inflicted between forces P_2 and P_3, namely between points 2 and 3 on the stem fragment investigated.

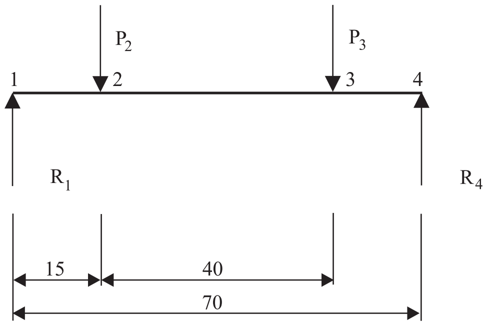

Fig. 2. Diagram of four-point bending load and the dimensional relationship between the supports and load-inflicted places

Rys. 2. Schemat obciążenia dla czteropunktowego zginania i relacje wymiarowe pomiędzy podporami i miejscami zadawanego obciążenia

The visualization of the research stand upon the start of research is given in Fig. 3a, and its completion in Fig. 3b. The research made use of the universal testing machine INSTRON 8874 (Instron, High *Wycombe*, England) in which the load-inflicted element was mounted on the actuator controlled by displacement. The actuator displacement velocity was 5 $mm \cdot min^{-1}$. During the trial there was recorded the input load in N and the actuator displacement as a sample flexion in mm. Both quantities were measured and recorded at the frequency of 2 Hz, which usually for a single sample was about 100 pairs of measurement points. The measurement point pairs made it possible to plot the load variation P ($P = P_2 = P_3$) – sample deflexion. Maximum load P_{max} determined from those plots allowed for determining the maximum value of inflicted bending moment M_{gmax}, according to the relationship: $M_{gmax} = 15 \cdot P_{max}$, where 15 mm is the value corresponding to the distance between the reaction of the support and the load. Determining the value of the damaging bending moment, corresponding to M_{gmax}, there was calculated maximum bending stress σ_{max} in the sample cross-section according to the following relation:

$$\sigma_{max} = M_{gmax}/W_{yśr} \text{ [MPa]}$$

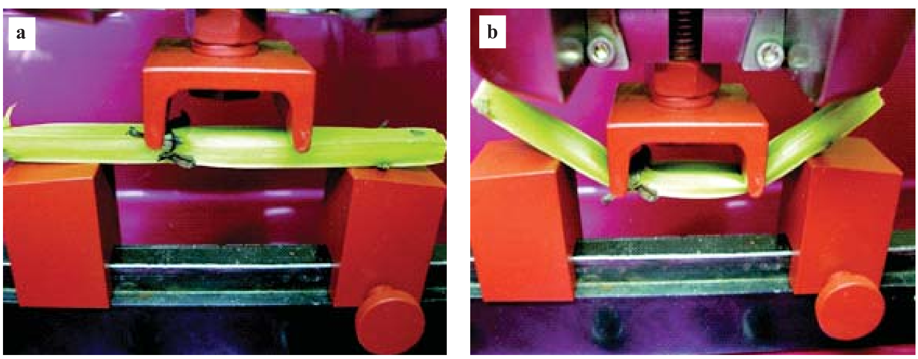

Fig. 3. Faba bean stem section bending before and after testing

Rys. 3. Zginanie fragmentu łodygi bobiku przed i po wykonaniu badania

For the entire plants there were also defined the following morphological traits: the stem height, setting height of the 1st pod (length of the section from the soil surface to the first pod), length of the fruit-bearing shoot, thickness of the stem and its wall and the internal diameter of the stem and the dry weight of the entire plant on the harvest day. The results were exposed to the analysis of variance for the randomised block design and the Tukey test was used to evaluate the significance of differences at P = 0.05.

The research period weather conditions were different for faba bean plant development and yielding (Table 1). The weather conditions in 2008 were exceptionally unfavourable, especially at the initial growth period, and then at the generative phase. Starting from the third decade of April to mid-July semi-drought and drought was reported; the average total rainfall over that period was much lower than the multi-year mean. In 2009 after no rainfall in April, in successive months there were noted good rainfall conditions for faba bean and lower rainfall in August was favourable to the steady completion of vegetation. Favourable moisture conditions (except for June) and temperature conditions were also reported in 2010. However, excessive rainfall in July and August made plant ripening more difficult. The beginning of physiological maturity and full maturity were reported for the seeds of traditional cultivar Neptun in successive research years, respectively, July 24, 30 and July 24 as well as August 4, 28 and 16, and the self-completing cultivar, Granit – 3-5 days earlier.

Table 1. Mean air temperature and rainfall according to the Mochełek Experimental Station
Tabela 1. Średnia temperatura powietrza według Stacji Badawczej w Mochełku

Specification Wyszczególnienie	Year Rok	Month – Miesiąc					
		April kwiecień	May maj	June czerwiec	July lipiec	August sierpień	September wrzesień
Mean air temperature, °C Średnia temperatura powietrza	2008	7.6	13.2	17.6	19.2	17.8	12.4
	2009	9.8	13.2	14.5	18.6	18.2	13.7
	2010	7.8	11.5	16.7	21.6	18.4	12.2
Mean air temperature in 1949-2009, °C Średnia temperatura powietrza w latach 1949-2009		7.3	12.8	16.3	18.0	17.4	13.2
Rainfall, mm Opady	2008	38.7	11.5	15.5	58.7	95.5	20.2
	2009	0.40	85.3	57.4	118.0	17.6	34.4
	2010	33.8	92.6	18.1	107.4	150.7	74.7
Rainfall in 1949-2009, mm Opady w latach 1949-2009		28.0	41.7	53.4	70.8	52.0	41.0

RESULTS AND DISCUSSION

Mechanical stem properties are cultivar-specific and depend on the development stage of the plant and correlate with the plant resistance to lodging [Haman and Kostankiewicz 1999, Skubisz 2002, 2008, Ince *et al.* 2005]. As reported by COBORU [Osiecka and Wiatr 2010], lodging in traditional faba bean cultivars (the average plant height of 129 cm) is greater than in the self-completing ones (103 cm), however, at the physiological seed maturity, when applying the 9-degree scale, it scores 7.61 and 7.97, and right before harvest – 6.65 and 7.27, and for the cultivars investigated – 7.5 and 6.6 as well as 8.1 and 7.6, respectively. In the present research no plant lodging was reported at all even though the plants differed significantly in terms of most morphological traits (Table 2). The plants of the traditional faba bean cultivar, Neptun, were significantly higher and showed a greater setting height of the 1st pod as well as the length of the fruit-bearing shoot and the dry weight of the above-ground part than in the plants of the self-completing cultivar, Granit. Of all the morphological traits, the evaluation date (the degree of seed maturity) of the stem resistance to bending also differentiated 4 of them significantly. With ripening, there were noted a lower mean height and thickness as well as the wall thickness and the dry weight of the above--ground plant part (Table 3). As a result of aging of monocarpic plants there are observed, next to considerable changes in the cell structure and in the hormonal management in leaves, also a water loss in the stems and above-ground dropping of organs [Górecki *et al.* 1999] and, at the same time, changes in their physical properties [Lisowski 2010].

Table 2. Differentiation in the morphological faba bean stem traits studied
Tabela 2. Zróżnicowanie badanych cech morfologicznych łodygi bobiku

Trait – Cecha	Cultivar – Odmiana		Mean Średnia
	Neptun	Granit	
Plant height, cm Wysokość rośliny	94.2 a	79.0 b	86.7
Height of the first pod setting, cm Wysokość osadzenia pierwszego strąka	45.6 a	41.1 b	43.6
Fruit-bearing shoot length, cm Długość pędu owocującego	48.9 a	38.5 b	43.7
Stem thickness, mm Grubość łodygi	8.81 a	8.64 a	8.73
Internal stem diameter, mm Wewnętrzna średnica łodygi	6.70 a	6.53 a	6.62
Stem wall thickness, mm Grubość ściany łodygi	1.60 a	1.64 a	1.62
Above-ground dry weight of plant, g Sucha masa części nadziemnej rośliny	20.8 a	19.3 b	20.0

Means followed by the same letters did not differ significantly at P = 0.05 – średnie oznaczone tymi samymi literami nie różniły się istotnie przy P = 0,05

Section modulus Wy [Kolowca *et al.* 2009, Lisowski 2010, Niezgodziński and Niezgodzińska 2010] and maximum bending stress σ_{max} [Chattopadhyay and Pandey 1999, Skubisz 2002, 2008, Ince *et al.* 2005, Wang *et al.* 2006, Skubisz *et al.* 2007, Guo *et al.* 2008, Tavakoli *et al.* 2009] are among the basic strength parameters used in the mechanical engineering and the design of various materials, including also the evaluation of resistance of plant stems to lodging. Section modulus Wy is a quotient of the moment of inertia of that cross-section against the neutral axis (crossing the centre of gravity of the cross-section) by the distance from that axis of the most distant element, which belongs to the cross-section, and maximum bending stress σ_{max} determines the stem resistance to bending.

Table 3. Effect of seed maturity on the morphological traits of faba bean plants
Tabela 3. Wpływ dojrzałości nasion na cechy morfologiczne roślin bobiku

Trait – Cecha	Seed maturity stage – Faza dojrzałości nasion		Mean Średnia
	beginning of physiological seed maturity – początek dojrzałości fizjologicznej nasion	full seed maturity pełna dojrzałość nasion	
Plant height, cm Wysokość rośliny	89.8 a	83.5 b	86.7
Height of the first pod setting, cm Wysokość osadzenia pierwszego strąka	43.6 a	43.0 a	43.3
Fruit-bearing shoot length, cm Długość pędu owocującego	46.6 a	40.7 a	43.7
Stem thickness, mm Grubość łodygi	9.36 a	8.09 b	8.73
Internal stem diameter, mm Wewnętrzna średnica łodygi	6.74 a	6.50 a	6.62
Stem wall thickness, mm Grubość ściany łodygi	1.70 a	1.54 b	1.62
Above-ground dry weight of plant, g Sucha masa części nadziemnej rośliny	22.5 a	17.5 b	20.0

Means followed by the same letters did not differ significantly at P = 0.05 – średnie oznaczone tymi samymi literami nie różniły się istotnie przy P = 0,05

In the present research the mean value of index Wy was 107.7 mm^3 and it was significantly higher at physiological seed maturity (128 mm^3) than at full seed maturity (87.4 mm^3), however, there was noted no significant variation in that trait in the faba bean cultivars investigated (Table 4). On the other hand, maximum bending stress σ was significantly differentiated neither by the measurement date nor the faba bean cultivar. The average value did not exceed 8 MPa; from 13.0 MPa in 2008 to 5.09-5.72 MPa, respectively, in successive years. Interestingly, over 2009 and 2010 the present research was made in the weather conditions similar and favourable to faba bean plants and in 2008 when the plants, at the total height of 46 cm, due to considerable rainfall deficit and high temperature, reached their maturity fast. And thus in 2008 value σ_{max} was very high (13 MPa), namely 2.5-3-fold higher than the means for 2009 and 2010. According to Ince *et al.* [2005] value σ_{max} increased with a decrease in the stem moisture on the measurement day, which was also observed in the present research with a delay in the measurement date to the stage of full seed maturity. Similar relationships were also noted for barley reported earlier [Tavakoli *et al.* 2009], wheat [Esehaghbeygi *et al.* 2009] and for maize [Guo *et al.* 2008]. As reported by Skubisz [2002] investigating pea, mean value of σ_{max} was 7.27 MPa and it decreased slightly with an increase in the stem measurement point height. Pea stems, generally with a high tendency to lodging, show lower bending stress σ_{max} in the middle part of the stem than at its base or in the apical part, however, both traits depend on the genetic properties of the cultivars.

Table 4. Mean values of Wx and σ indices of the stems in the faba bean cultivars studied depending on the seed maturation stage
Tabela 4. Średnie wartości wskaźników Wx i σ łodyg badanych odmian bobiku w zależności od fazy dojrzałości nasion

Cultivar Odmiana	Seed maturity stage – Faza dojrzałości nasion		Mean Średnia
	beginning of physiological maturity – początek dojrzałości fizjologicznej	full seed maturity pełna dojrzałość nasion	
	Wx		
Neptun	138	91.9	114.9 a
Granit	118	82.9	100.5 a
Mean	128 A	87.4 B	107.7
	σ		
Neptun	8.12	9.58	8.85 a
Granit	5.90	8.16	7.03 a
Mean	7.01 A	8.87 A	7.94

Means followed by the same letters did not differ significantly at P = 0.05 – średnie oznaczone tymi samymi literami nie różniły się istotnie przy P = 0,05

The morphological traits of the faba bean stems were positively correlated with stem section modulus W_y and negatively correlated with maximum bending stress σ (Table 5). The highest values of the coefficient of correlation of morphological and strength traits of the faba bean stems are given in Table 5.

Table 5. Correlation coefficients between morphological faba bean plant traits and stem section modulus (Wy) and stem resistance to bending (σ)
Tabela 5. Wskaźniki korelacji między cechami morfologicznymi roślin bobiku i wskaźnikiem wytrzymałości przekroju łodygi na zginanie (Wy) a wskaźnikiem odporności łodygi na zginanie (σ)

Morphological plant traits – Cechy morfologiczne roślin	Wy	σ
Plant height – Wysokość roślin	0.848**	-0.696**
Height of the 1st pod setting – Wysokość osadzenia pierwszego strąka	0.756**	-0.703**
Length of pods bearing stem – Długość łodygi ze strąkami	0.780**	-0.608**
Stem thickness – Grubość łodygi	0.982**	-0.906**
Internal stem diameter – Wewnętrzna średnica łodygi	0.941**	-0.902**
Stem wall thickness – Grubość ściany łodygi	0.481	-0.696*
Above-ground dry weight of plant Sucha masa nadziemnej części rośliny	0.601*	-0.448

* r significant at P = 0.05 – r istotne przy P = 0,05
** r significant at P = 0.01 – r istotne przy P = 0,01

The analysis of regression equations shows that the increase in the total stem length and its part from the soil surface to the setting of the 1st pod and in the length of fruit-bearing shoot by 10 cm were accompanied by an increase in the value of stem section modulus (W_y), respectively by 14.1; 17.2 and 27.0 mm^3 (Fig. 4a) and a decrease in the resistance to bending – 0.95; 1.04 and 1.07 MPa, respectively (Fig. 4b). Similarly for the stem thickness, each of its 1 mm increases resulted in an increase in the value of W_y

by 33.7 mm^3 and a decrease in σ_{max} by 2.24 MPa (Fig. 5). However, the highest degree of determination was recorded for the relationship between the internal stem diameter and the strength traits investigated (Fig. 6). An increase in the stem diameter by 1 mm resulted in an increase in the value of Wy by 44 mm^3 and a decrease in maximum bending stress by 3.26 MPa, which means that in faba bean, similarly as in other species, the strength traits of plants, including resistance to lodging, are determined by the stem thickness and its internal diameter [Haman and Konstankiewicz 1999, Lisowski 2010].

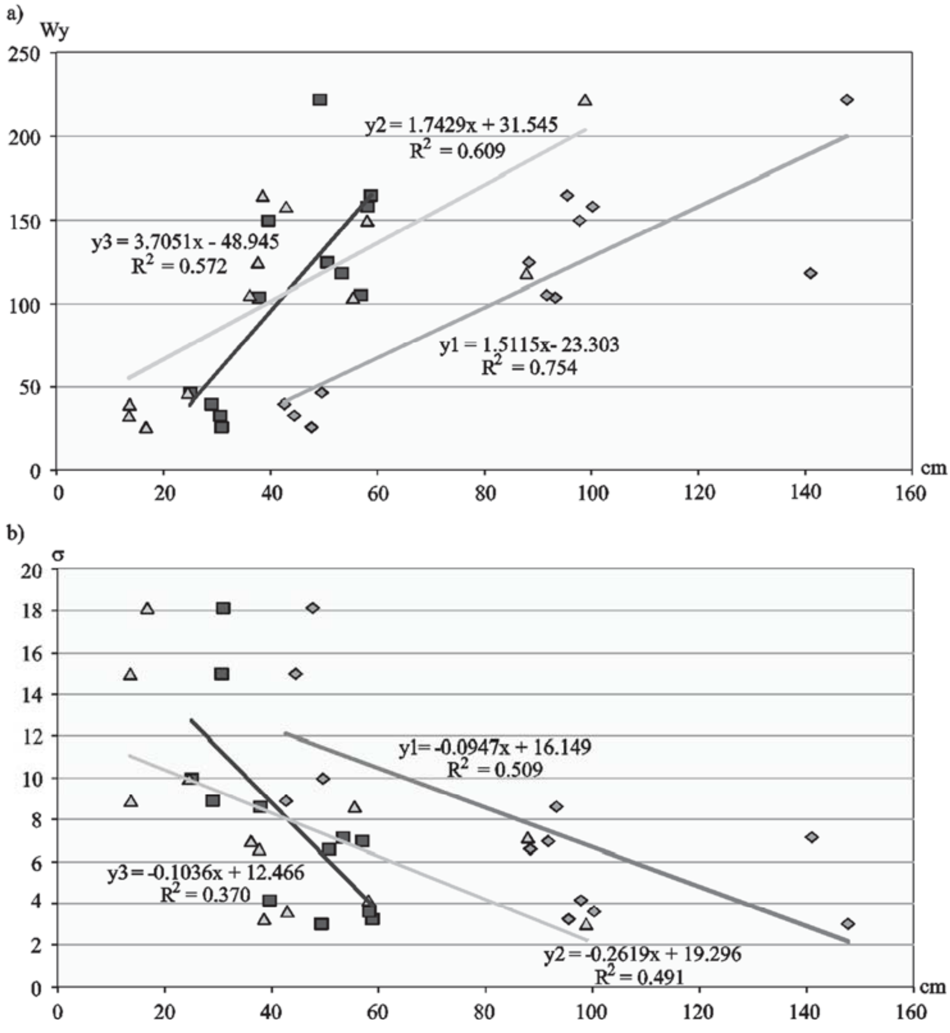

Fig. 4. Effect of the plant height (y1), the 1st pod setting height (y2) and the fruit-bearing shoot length (y3) on: a) stem section modulus Wy, b) resistance of the stem to bending σ

Rys. 4. Wpływ wysokości roślin (y1), wysokości osadzenia 1. strąka (y2) i długości pędu owocującego (y3) na: a) wskaźnik wytrzymałości przekroju łodygi na zginanie Wy, b) wskaźnik odporności łodygi na zginanie σ

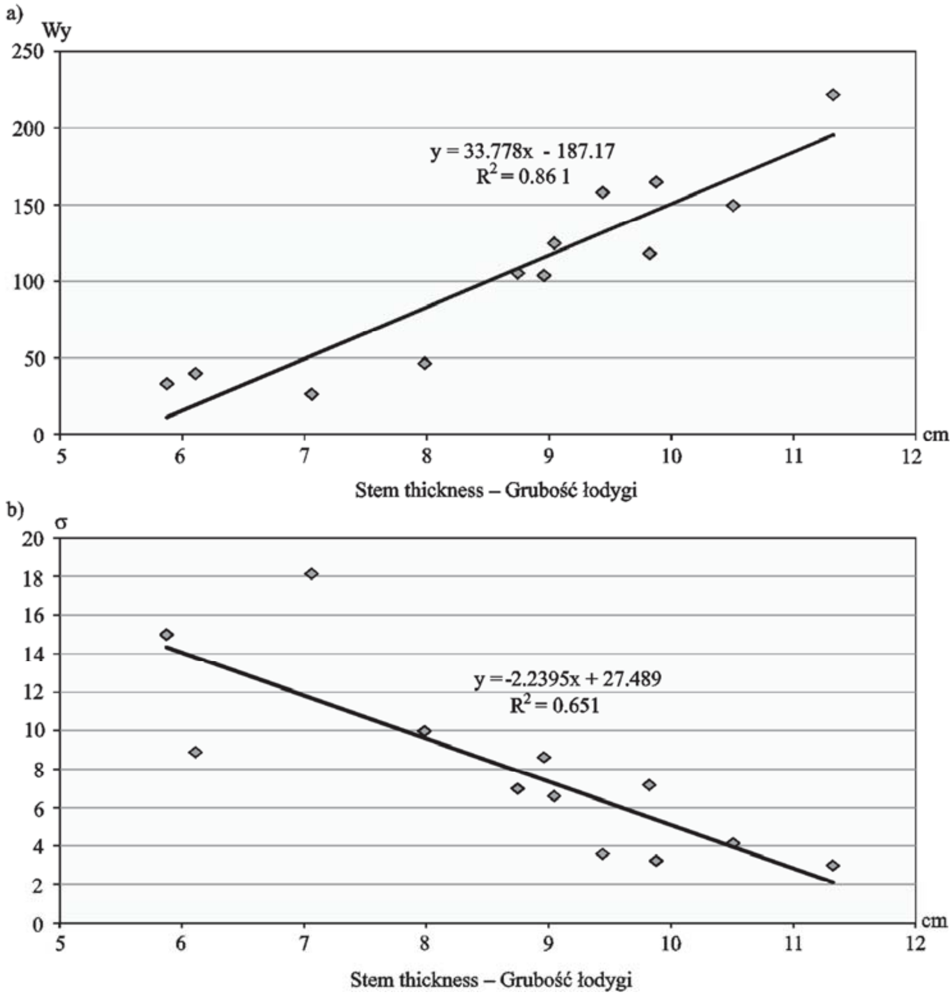

Fig. 5. Effect of the faba bean stem thickness on: a) stem section modulus Wy, b) resistance of stem to bending σ

Rys. 5. Wpływ grubości łodygi bobiku na: a) wskaźnik wytrzymałości przekroju łodygi na zginanie Wy, b) wskaźnik odporności łodygi na zginanie σ

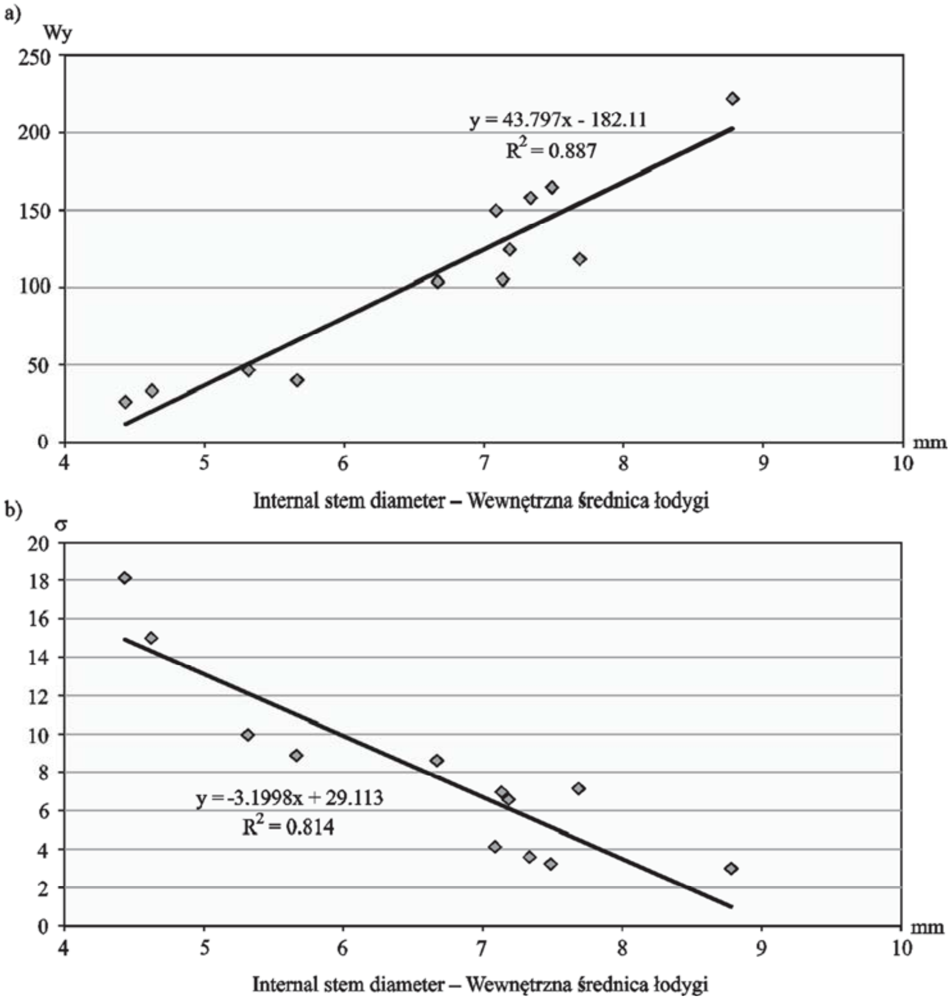

Fig. 6. Effect of the internal faba bean stem diameter on: a) stem section modulus Wy, b) stem resistance to bending σ

Rys. 6. Wpływ wewnętrznej średnicy łodygi bobiku na: a) wskaźnik wytrzymałości przekroju łodygi na zginanie Wy, b) wskaźnik odporności łodygi na zginanie σ

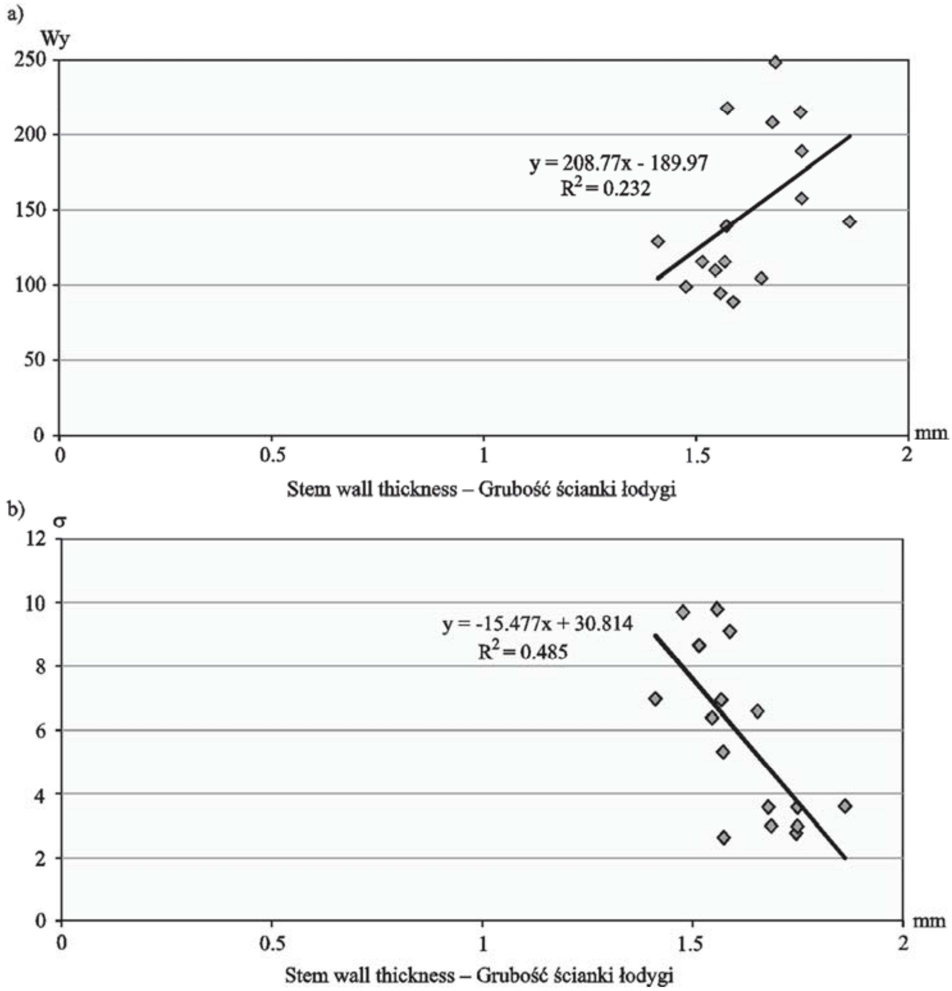

Fig. 7. Effect of faba bean stem wall thickness on: a) stem section modulus Wy, b) stem resistance to bending σ

Rys. 7. Wpływ grubości ścianki łodygi bobiku na: a) wskaźnik wytrzymałości przekroju łodygi na zginanie Wy, b) wskaźnik odporności łodygi na zginanie σ

CONCLUSIONS

1. The faba bean cultivars investigated, despite a lack of differences in the degree of lodging, differed significantly in terms of most morphological traits of stems.
2. At the physiological maturity of seeds, the dry weight of the above-ground part of 1 plant and the stem thickness were significantly higher than at full seed maturity.
3. The average stem section modulus at the physiological seed maturity was significantly higher than at full maturity. On the other hand, the average maximum bending stress was significantly differentiated neither by the measurement date nor by the faba bean cultivar.

4. The stem strength indices investigated were negatively correlated with each other. An increase in the total stem length and the setting height of the 1st pod and the length of the fruit-bearing shoot as well as the stem thickness and its internal diameter were accompanied by an increase in stem section modulus W_y and a decrease in the stem resistance to bending.

5. The stem strength traits investigated were affected by the weather pattern determining the growth of plants, the height and the morphological structure of the stem, especially its thickness and internal diameter.

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ODPORNOŚĆ ŁODYG TRADYCYJNEJ I SAMOKOŃCZĄCEJ ODMIANY BOBIKU (*Vicia faba* SPP. *minor*) NA ZGINANIE CZ. I. WPŁYW BUDOWY MORFOLOGICZNEJ ŁODYG

Streszczenie. Przedmiotem badań były rośliny dwóch odmian bobiku: tradycyjnej Neptun i samokończącej Granit, zebrane w latach 2008-2010 z pola doświadczalnego Stacji Badawczej w Mochełku, należącej do Wydziału Rolnictwa i Biotechnologii UTP. Analizę cech morfologicznych wykonano w dwóch fazach dojrzałości nasion – fizjologicznej i technicznej. Cechy wytrzymałościowe łodyg – wskaźnik wytrzymałości przekroju łodygi na zginanie W_y i maksymalne obciążenie zginające σ określono na maszynie wytrzymałościowej INSTRON 8874 (High *Wycombe*) na 80 mm fragmentach łodyg pobranych z międzywęźla tuż pod pierwszymi strąkami. Odmiany bobiku, pomimo braku różnic w stopniu wylegania, różniły się istotnie pod względem 5 spośród 7 badanych cech morfologicznych. W dojrzałości fizjologicznej nasion średnia odporność przekroju łodygi na zginanie W_y była istotnie wyższa niż w dojrzałości pełnej. Z kolei średnie maksymalne naprężenie zginające σ (odporności łodygi na zginanie) nie było istotnie różnicowane ani przez stopień dojrzałości nasion, ani odmianę bobiku. Wzrostowi całkowitej długości łodyg oraz wysokości osadzenia 1. strąka i długości pędu owocującego, a także grubości łodygi i jej wewnętrznej średnicy towarzyszyło zwiększanie wskaźnika odporności przekroju łodygi na zginanie i zmniejszanie odporności łodygi na zginanie.

Słowa kluczowe: bobik, cechy morfologiczne, typ odmiany, wytrzymałość łodyg na zginanie

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